THE MARINE CHEMISTRY OF SØRFJORDEN, WEST NORWAY.

by

Jens Malvin Skei, cand. mag. (Bergen)

Thesis presented for the degree of DOCTOR OF PHILOSOPHY of the University of Edinburgh, in the Faculty of Science.

1975

ABSTRACT

Sörfjorden is an elongate (37 km long), deep (400 m) and well ventilated tributary fjord of Hardangerfjorden on the south-west coast of Norway. Metallurgical and chemical industries at its head discharge various effluents which cause pollution of the waters and the sediments of the fjord.

Information on salinity, temperature, dissolved oxygen, phosphate and silicate have been used to establish a four-layer water flow. The upper water circulation is promoted by river runoff; water movements at greater depths are controlled by deep water inflows. The pattern of water exchange has been investigated at different seasons when runoff and hence circulation varied considerably. Surface flow is greatest during summer and least in early spring. In autumn an invasion of shallow coastal water pervades the fjord causing an outflow at intermediate depths carrying pollutants with it. The midwater outflow of contaminated water observed in summer is a result of bottom water flushing and vertical displacement.

While the geochemistry of Si, Al, Ti, K and Mg in the sediment conforms to small changes in lithology, Fe, Ca and P as well as Cu, Pb and Zn show considerable surface enrichments, especially towards the head of the fjord which are the result of sedimentation of industrial waste.

The composition of suspended particulate matter (>0.4 μ) contained in various watermasses has been investigated in order to

understand the pattern of inflow and outflow of waters and the extent of natural (terrigenous, biogenous and authigenic) and contaminated loadings in them. Furthermore, it was hoped that these investigations would illustrate the mode of sedimentation and the interaction of the particulate matter with the bottom sediment. Strong inter-element relationships between K, Mg, Ti and Al occur in the alumino-silicates. Particulate biogenous constituents (Si, Ca, P and S) show seasonal change and vary with the amount and type of standing crop. Their vertical distribution demonstrates a different behaviour with respect to dissolution and decomposition. Skeletal constituents (Si and Ca) provide evidence of a slow rate of dissolution in contrast to organic matter (P and S) which is mostly consumed in the surface 100 m of water. Substantial amounts of Ca and P from industrial effluent affect the southern parts of the fjord. It is believed that Ca here is an inorganic precipitate of calcite derived from solution of gypsum in the industrial effluent.

The distribution of particulate authigenic phases (Fe and Mn) suggests flocculation or precipitation of these at the halocline in some southern waters. In the bottom waters of the fjord they occur by resuspension of the sediment, followed by preferential settling of alumino-silicates. As a consequence, the bottom nepheloid layer is enriched in finely dispersed authigenic phases (e.g. Fe-Mn oxides). In contrast, the abundance of non-silicate Fe at intermediate depths is due to dispersal of Fe-suspensions discharged from a zinc plant. Particulate and dissolved Pb and Zn indicate outflow of contaminated water at two levels in the fjord; at the surface and at intermediate

depths.

The mineralogy and chemistry of the particulate matter of the bottom nepheloid layer and the bottom sediment are poorly related and support the argument that the bulk of the sediments accumulated during periods of exceptional runoff conditions (e.g. storms, heavy snowmelting), when rivers transport very coarse material (sand and silt). The composition of this detritus is expected to be different from that of particulate matter settling during 'normal conditions', as occurred during the sampling of the fjord.

An attempt has been made to calculate mass-balance for particulate Al (sediment) and dissolved Zn (pollutant) by assuming that river flow and suspended load are linearly related. The results emphasize the importance of studies of river flow and their carrying capacity during various runoff conditions.

CONTENTS

TEXT

PART I

INTRODUCTION

Geochemical studies of fjords in the past have been largely confined to problems of anoxicity in poorly ventilated fjord basins. Oxic fjords, which outnumber those showing anoxic features, have been less studied with respect to geochemistry. Studies of such fjords have generally been restricted to hydrographic or biological surveys. However, considerable seasonal and areal variations in hydrography and water circulation as well as productivity make the interpretation of such occasional surveys difficult. It was therefore thought that an integrated study of the hydrography, hydrochemistry, the chemistry of suspended particulate matter and the geochemistry of the sediments in a deep, well-ventilated fjord would elucidate the following problems:

1) transport of sediments at various runoff conditions.
2) identification of watermasses and flow by means of hydrographic parameters and suspended particulate matter load and composition.
3) seasonal and depth variations of dissolved particulate biogenous components and their relevance to the breakdown of organic and skeletal matter.
4) bottom water flushing, displacement of watermasses and the composition of bottom nepheloid layers with respect to that of the bottom sediments.

Because of the broadness of the study it is inevitable that parts of it have been treated relatively superficially (e.g. sediment

geochemistry) while other parts have been given a higher priority (e.g. the chemistry of the suspended particulate matter). The choice of priority was made on the basis of the application of particulate matter chemistry and its relevance to an understanding of the problems outlined above.

Fjord environments are in danger of becoming polluted as a consequence of their use as recipients for industrial and domestic waste. For instance, fjords in Norway situated in areas where hydroelectric power is easily accessible attract metal processing industries to their shores. A typical example is Sörfjorden, West Norway, which receives various metallic and non-metallic wastes in large quantities.

As radioactive substances have been used to trace circulation in coastal and oceanic waters, so may industrial pollutants in fjords serve as tracers of fjord circulation. One of the aims in this study has been to demonstrate this. The usefulness of such tracer techniques is particularly appreciated when considering movements of watermasses at intermediate depths, where the circulation is badly defined due to the limitation of conventional methods (e.g. current measurements).

Physio-chemical reactions which may take place in the water are also little known. Such phenomena are seawater-fresh water interactions (precipitation, adsorption and desorption), aggregation and flocculation of particles and interactions between inorganic and organic phases (e.g. uptake of various elements by plankton). Most of the reactions mentioned above have been

simulated by several workers under laboratory conditions, but it is difficult to transpose such results to the natural environment. A better approach is to study these mechanisms in situ as far as it is possible. The chemical composition of particulate matter assists to some extent an understanding of these problems.

Another aspect of fjord research which is often overlooked is the mode of sedimentation, both of natural and pollutant substances. The deposition of sediment from various sources and by several mechanisms results in accumulation of sediments of wide ranges in physical properties and chemical composition. One of the intentions in this study was to compare the chemistry of sediments suspended in the river water and the waters of the fjord with that of sediments deposited on the seabed, in an attempt to elucidate the mode of sedimentation. It becomes clear that to understand fully the problems of sedimentation in fjords and the mass-balance of sediments, a much closer inspection of sediment input during a wide range of runoff conditions is necessary.

It follows that the complex nature of oxic fjords deserves a much more thoroughly integrated and inter-disciplinary study. Meanwhile, it may be concluded that fjords generally are unsuitable as recipients of wastes as their fate in fjords is unpredictable.

CHAPTER 1

INTRODUCTION TO THE AREA OF STUDY

1.1. Sörfjorden - general situation

Sörfjorden is situated 70 km to the south-east of Bergen, West Norway (Fig. 1.1). The fjord is a tributary to the large Hardangerfjorden complex. General information about Sörfjorden is given in Table 1.1.

Table 1.1. General information

Physical measurements		
Length		37 km
Width (average)		1.7 km
Surface area		$\sim 63\ km^2$
Maximum depth		400 m
Total volume[1]		$\sim 1 \times 10^{10}\ m^3$
Volume:	0-5 m depth	$3.15 \times 10^8\ m^3$
	5-20 m "	$9.3 \times 10^8\ m^3$
	20-150 m "	$5.6 \times 10^9\ m^3$
	150-250 m "	$2.9 \times 10^9\ m^3$
	250-400 m "	$7.6 \times 10^8\ m^3$
Annual precipitation[2]		2500 mm
Annual runoff[3]		$\sim 2.0 \times 10^9\ m^3$
Tidal amplitude[4]		< 1 m

1 The evaluation of the volume of Sörfjorden between various depth intervals is based on finding an average cross-sectional area and then multiplying by the length of the water body. The cross-sectional area is computed from the average of 9 cross-sections from various parts of the fjord.

2 Kolderup (1960).

3 Environmental Committee Report (1973). Histogram of river runoff in the river Opo (1972) is shown in Fig. 1.2.

4 Svines (1970).

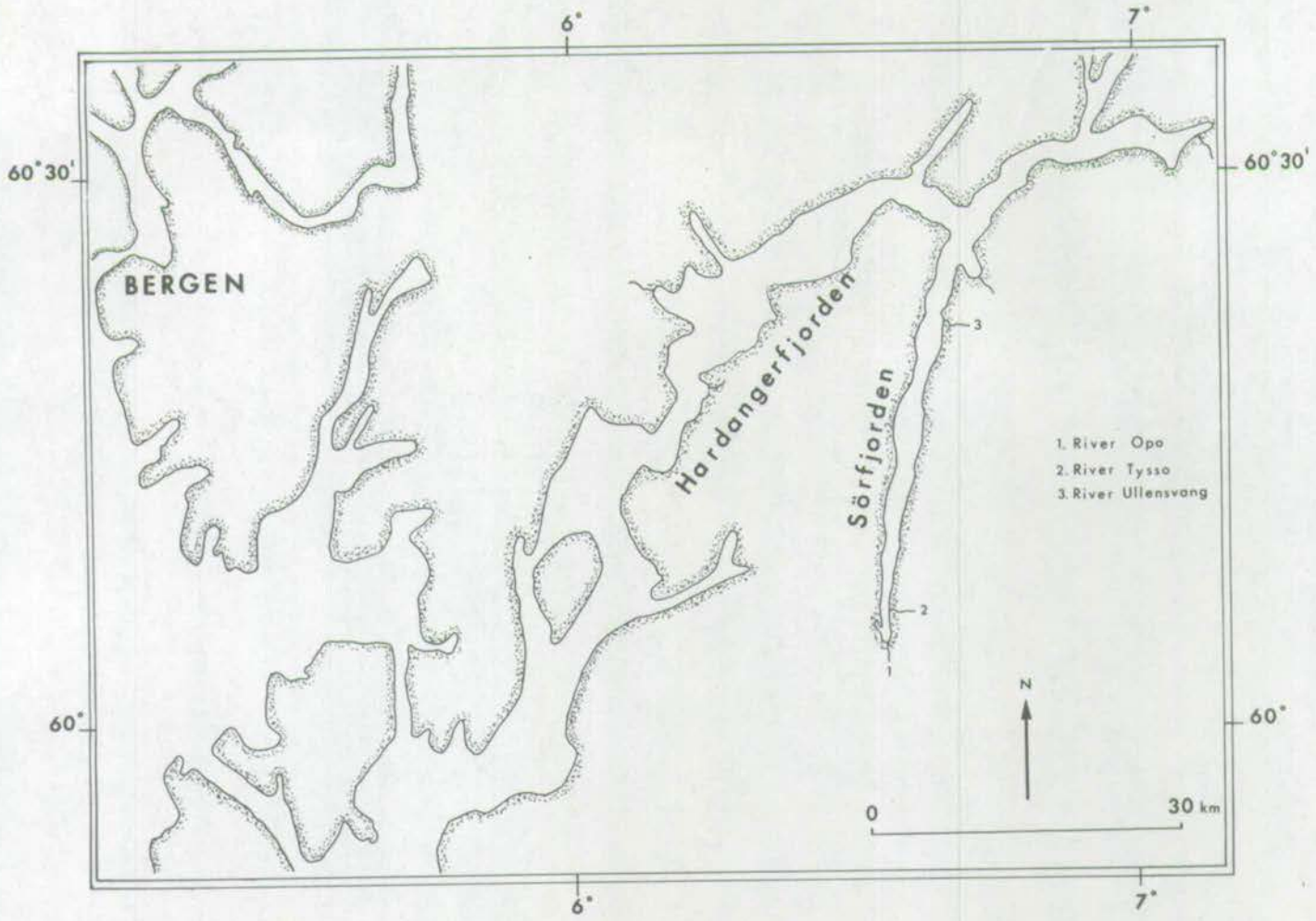


Fig. 1.1. Location of the area of study.

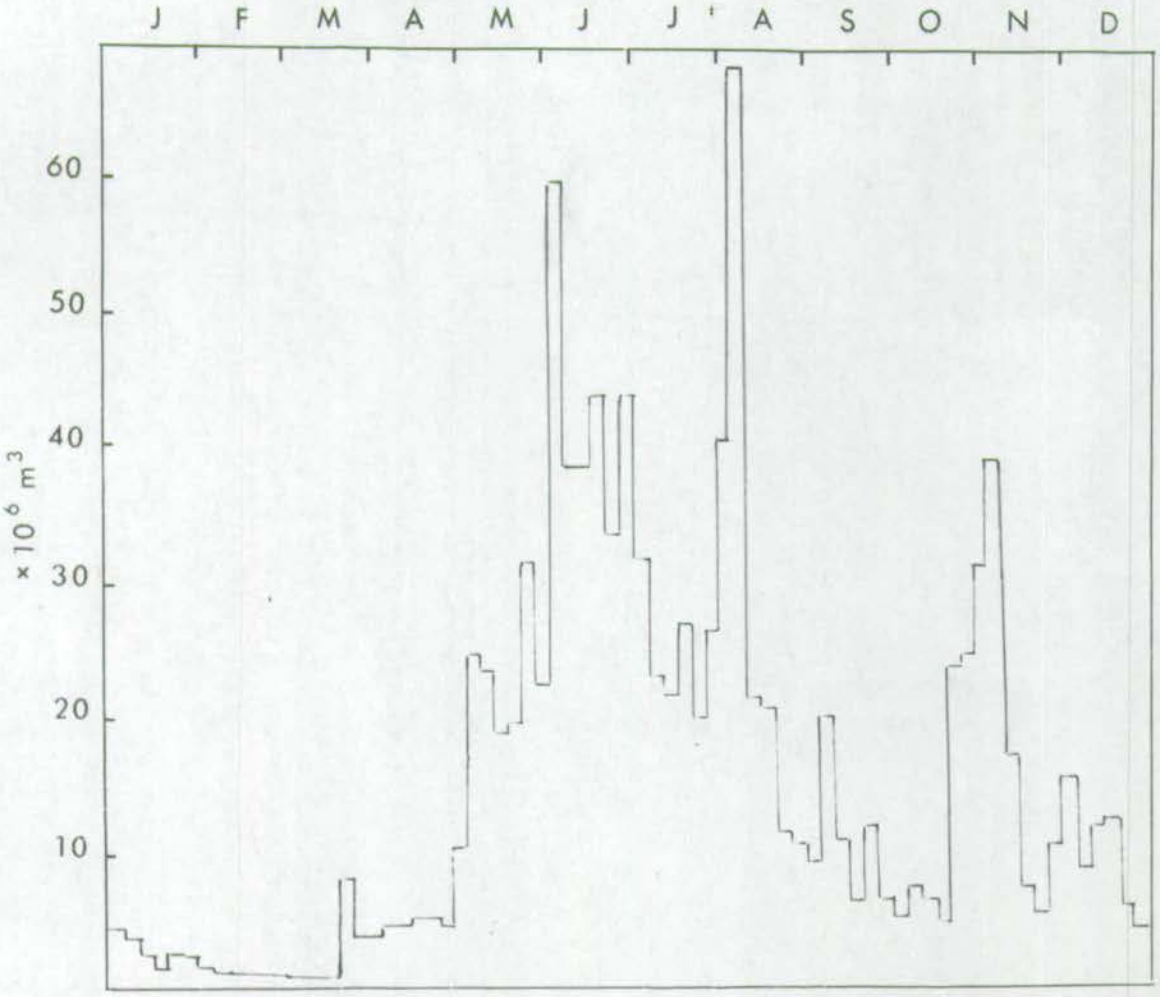


Fig. 1. 2. Histogram showing the weekly variation in river runoff from the river Opo into Sörfjorden during 1972 (after Svendsen, 1973).

1.2. Local geology and surface runoff

Sörfjorden follows a zone of structural weakness (N-S) and is founded in Pre-Cambrian granites and gneisses as well as altered volcanic and sedimentary rocks consisting of quartzite, quartz diorite, quartz porphyr, amphibolite and hornblende schists (Kvale, 1946).

The direction of Hardangerfjorden coincides to a great extent with the main Caledonian Structure, being surrounded by Pre-Cambrian rocks to the east similar to those found along Sörfjorden, and Cambro-Silurian mica-schists, phyllites and green schists to the west (Kolderup, 1960).

The Pleistocene deposits along the shores of Sörfjorden have been described by Kvistad (1965). These deposits are basically moraines, locally derived material with low clay content.

1.3. Geomorphology and bathymetry of Sörfjorden

According to Ahlmann (1919) Sörfjorden is the classical example of a fjord: long and narrow, steepsided, and possessing a sill at the entrance.

The longitudinal profile shown in Fig. 1.3 displays several flat basins interrupted by sills which rise some 50 m to 100 m above the basins. It is not known whether these sills are ridges of rock or remnants of terminal moraines. However, the most plausible explanation is that they consist of a rock core which during the Ice Age was covered by moraine material (Holtedahl, 1965).

Typical cross-sections of Sörfjorden are shown in

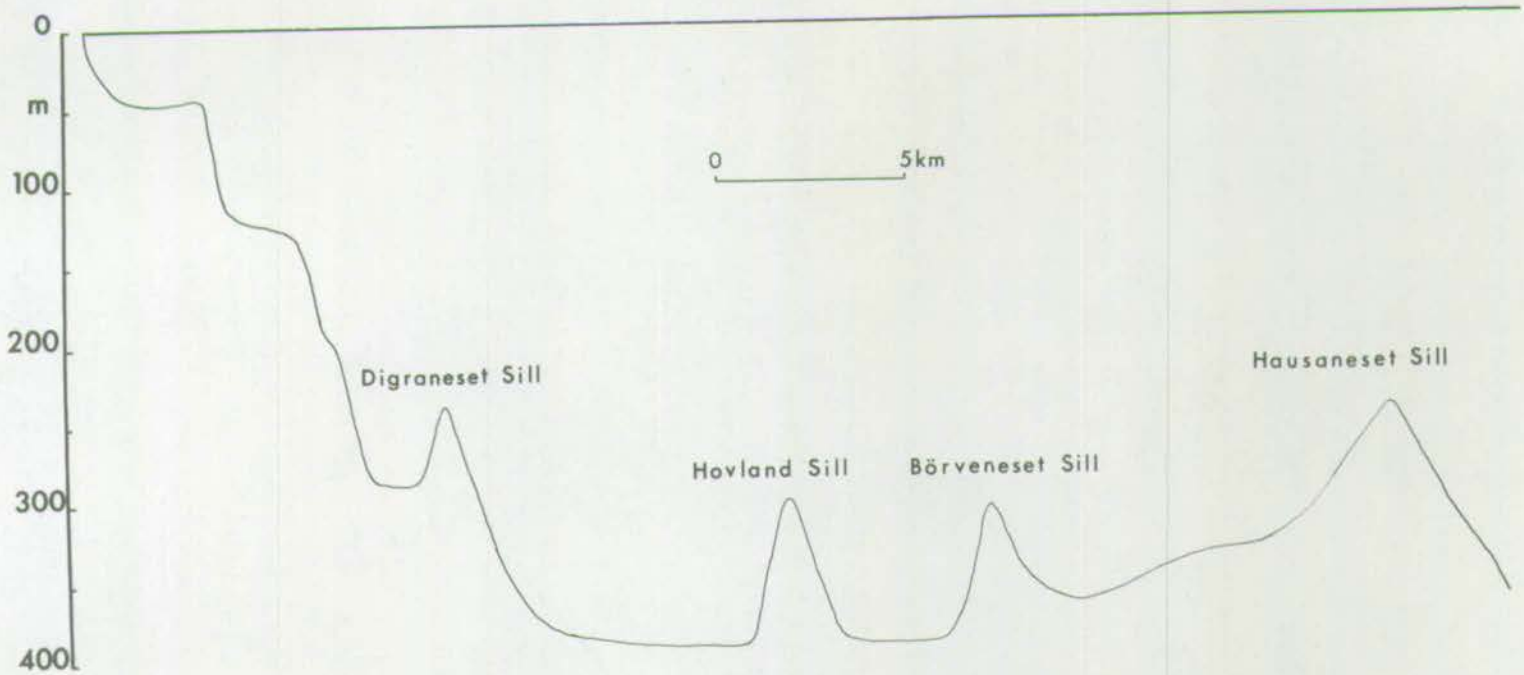


Fig. 1. 3. Longitudinal profile of Sörfjorden.

Fig. 1.4, demonstrating the characteristic U-shape across the wide flat basins and the V-shape across narrow stretches in the fjord. Both the longitudinal profile and the cross-sections were constructed from recordings made with a "Simrad" echo-sounder.

The freshwater enters the fjord via three rivers (Opo, Tysso and Ullensvang, Fig. 1.1) and an abundance of small streams. River Opo is the main freshwater contributor, its runoff being partly controlled by the Lake Sandvevann (Fig. 1.5). The second largest river, Tysso, is regulated and discharges a constant volume of 26 m^3/sec (Environmental Committee Report, 1973). On entering the fjord the river water tends to incorporate seawater (i.e. entrainment) which is transported out of the fjord. To maintain the volume continuity the seawater mixed into the surface flow is replaced by inflowing seawater immediately below (i.e. compensating current).

1.4. Industrial activities in the area

Three major industrial companies (see Fig. 1.5 for location) were established around the town of Odda in the beginning of this century. To cope with the enormous demand on electrical power, the river Tysso (Fig. 1.1) was regulated and a power station was built in 1916.

A specification of the chemical commodities produced by the respective companies (Fig. 1.5) is given in Table 1.2.

Fig. 1.4. Typical transverse sections, showing changes in shape and cross-sectional area of Sörfjorden.

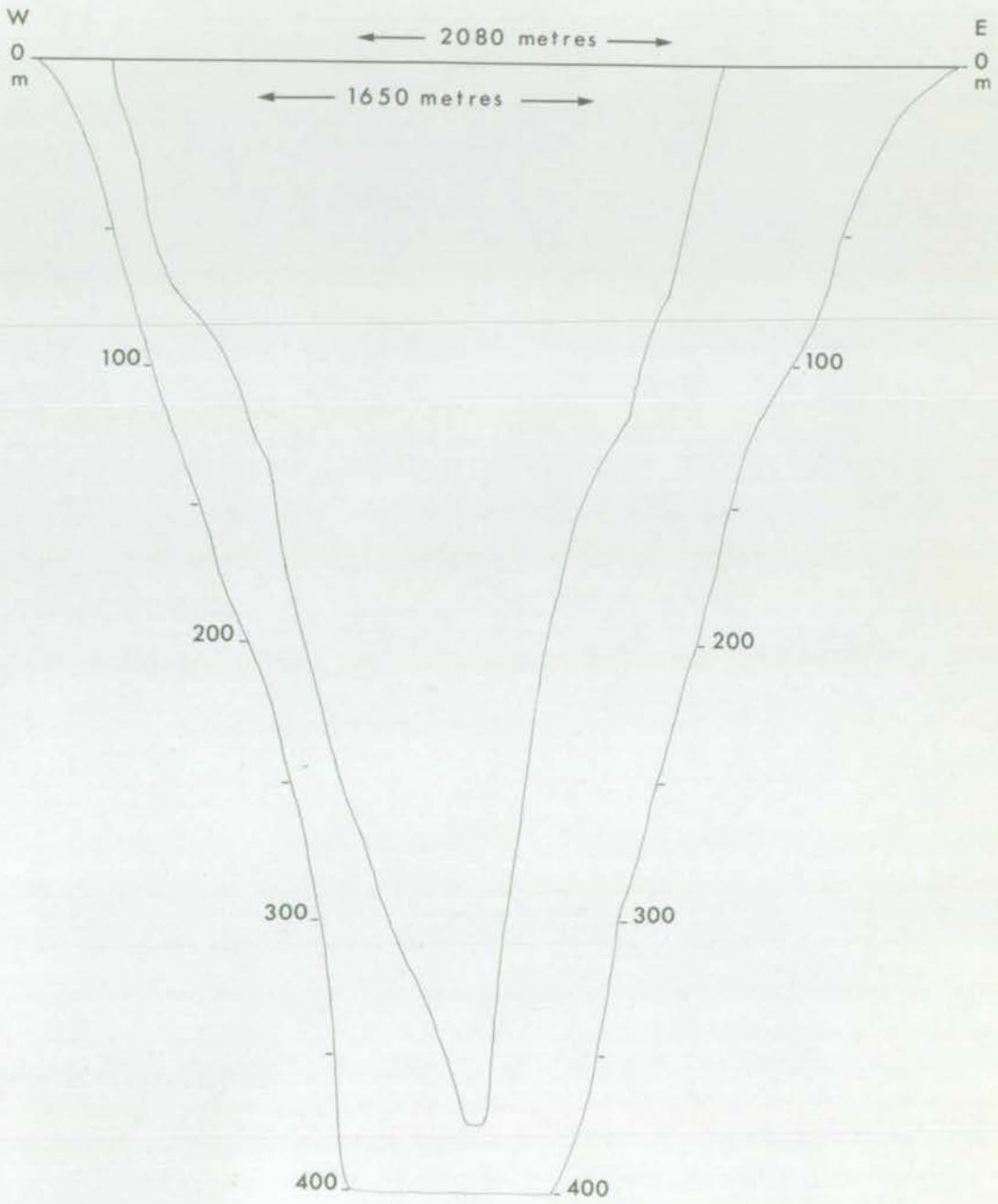


Table 1.2. Types of commodities being produced

Name of company	Production started	Types of products
Odda Smelteverk A/S (O.S.)	1908	aluminium
D.N.N. Aluminium A/S (D.N.N.)	1916	calcium carbide, calcium cyanamide, dicyanamide
Det Norske Zinkkompani (D.N.Z.)	1929	zinc, cadmium, phosphoric acid, aluminium fluoride

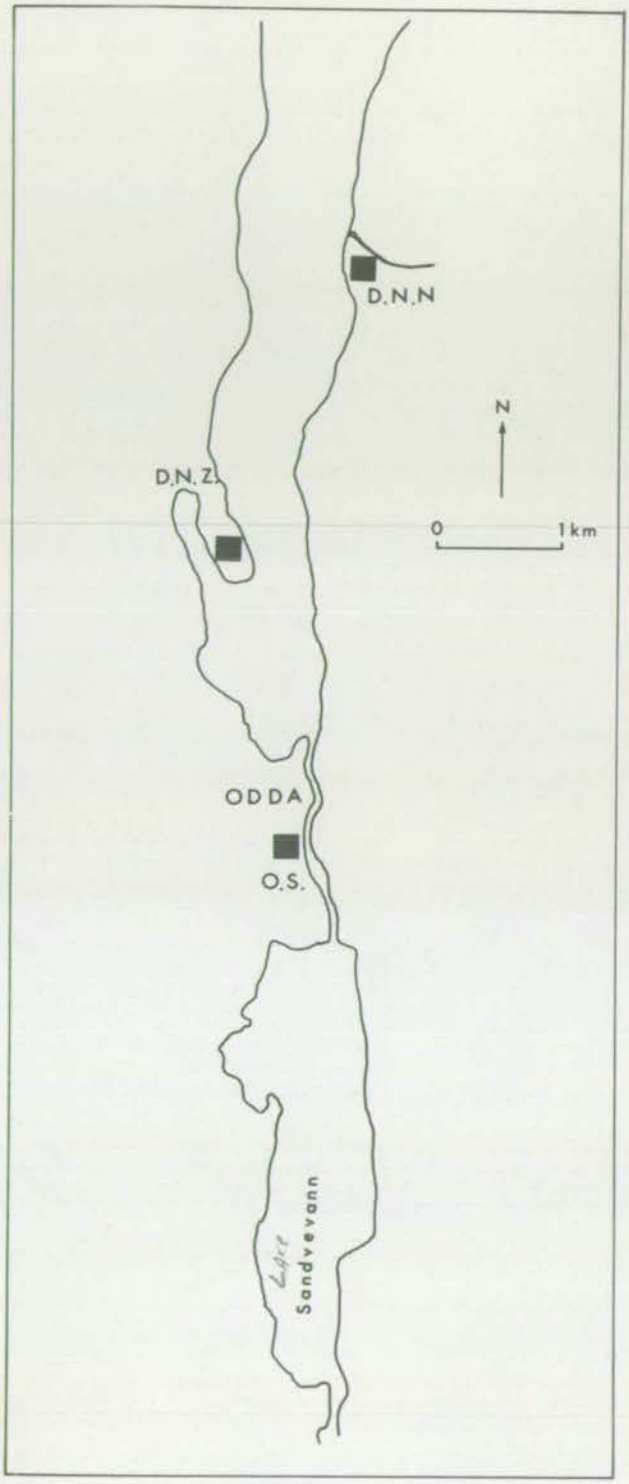


Fig. 1. 5. The situations of the three industrial companies (O. S., D. N. Z. and D. N. N.) (see Table 1. 2)

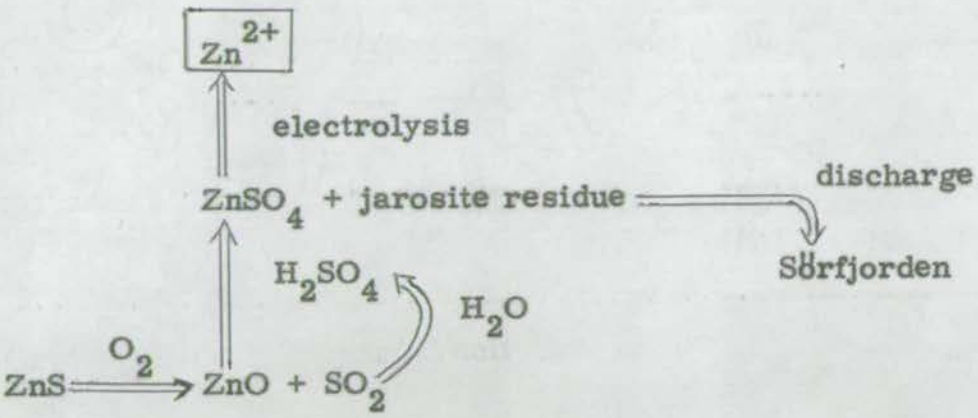
CHAPTER 2

THE DISCHARGE OF INDUSTRIAL WASTE INTO SØRFJORDEN

The industrial activities about the town of Odda commenced at the beginning of this century (see Table 1.2). Increased production of chemical commodities with time has caused increased pollution of the waters of the fjord and the atmosphere about Odda. Only within the last decade have new production methods created an improved product/waste ratio. For instance, the residual waste product from the Zn-production showed a significantly lower metal content when the 'jarosite-process' came into operation in 1968. Between the years 1954 and 1968 the waste discharged into the fjord contained ~10% Zn and Pb. In 1973 the metal content was reduced to ~3.2% Zn and ~2% Pb (Environmental Committee Report, 1973). With encouragement by the Environmental Committee of Odda (from 1970 to 1973), large investments have been made by the various industrial companies in their attempts to purify and recycle their waste.

2.1. Discharge of heavy metal waste

Heavy metals are almost exclusively discharged into the fjord from a zinc smelting plant (D.N.Z., Fig. 1.5), the metals being largely associated with jarosite residue. A schematic and simplified model of the Zn-processing method (since 1968) is shown below.



The annual amount of jarosite ($(NH_4)_2Fe_6(SO_4)_4(OH)_{12}$) discharged into the fjord by this process is ~27000 tons; the metal content in this residue is given in Table 2.1. As stated above, prior to 1973

Table 2.1. Heavy metals in the jarosite residue (1973) (after Environmental Committee Report, 1973)

Metal	Average concentrations (%)	% of total metal discharged
Zn	3.2	60
Cu	0.22	90
Cd	0.03	50
Pb	2	100
As	0.2	100
Sb	0.15	100
Ag	0.01	100

the Pb concentrations were some five times higher than shown in Table 2.1. Current processing techniques separate most of the Pb-Ag residue from the jarosite for storage on shore. Before discharge, the jarosite is mixed with seawater and pumped as a suspension containing 100 g/l (~10% by weight) of solids into the fjord. Approximately 600-800 m^3 per day of this suspension (i.e. 60-80 m^3 per day solid matter) of 1-20 μ grain size is discharged at ~15 m depth. Measurements of the suspension have shown that its density is close to 1.09 g/ml (Environmental Committee Report, 1973).

While a large proportion of the Pb and Zn associated with the jarosite occur as water soluble sulphates, other heavy metals present tend to occur as water insoluble compounds (e.g. Cu).

Besides jarosite, two other important sources of heavy metals exist; 1) leakage of dissolved metals from the Zn-processing plant, and 2) metals dissolved in the discarded acid. These discharges contain many dissolved metals, particularly Zn, Cd and Cu (see Table 2.2). Waste from leakage is introduced to the surface

Table 2.2. Heavy metals in waste water from leakages and in discarded acid (after Environmental Committee Report, 1973)

Metal	Average concentrations (%)	% of total metal discharged
	wastewater from leakage	
Zn	~1	25
Cu	~0.1	10
Cd	~0.1	50
	discarded acid	
Zn	~1	15
Cu	-	-
Cd	-	-

waters (0 m) of a small bay adjacent to the harbour basin (Fig. 1.5). The discharge point of the discarded acid is at ~10 m depth on the east side of the zinc plant.

Table 2.3 shows the daily amounts of metals and their respective chemical compounds being currently discharged into Sörfjorden.

Table 2.3. Metals in industrial waste discharged into Sörfjorden (1972) (after Environmental Committee Report, 1973)

Metal	Compound in waste	Discharged weight per day (in tons)
Zn	$ZnO.Fe_2O_3$, $ZnSO_4$	6
Cu	$CuSO_4$, CuO_2, Cu-jarosite	0.3
Cd	$CdSO_4$, CdS, $CdO.Fe_2O_3$	0.03
Pb	$PbSO_4$	4.5
As	$FeAsO_4$	0.09
Sb	$FeSbO_4$	0.06
Hg	HgS, HgSe, Hg_2Cl_2, Hg, Hg^{2+}	0.003
Fe	$(NH_4)_2 Fe_6(SO_4)_4(OH)_{12}$, $ZnO.Fe_2O_3$, Fe_2O_3	23
Mn	$MnSO_4$, MnO_2	0.15

2.2. Discharge of light elements and non-metallic waste

While most attention will be paid to the distribution of heavy metals in Sörfjorden, the discharge of several light elements and indeed some non-metals is bound to have a significant impact on the fjord environment. Also their presence adds to the input of many substances entering the fjord by natural means. Table 2.4 shows the daily input of some of these substances, the most prominent being Ca, P, S and to a lesser extent Al.

Of the total amount of Ca, about 50% resides in gypsum, which is discharged at 8 to 10 m and 20 m depth. Approximately 147,000 tons of gypsum are discharged annually, of which ~35%

Table 2.4. Light and non-metallic elements in industrial waste discharged into Sörfjorden (1972) (after Environmental Committee Report, 1973)

Element	Compound in waste	Discharged weight per day (in tons)
Ca	$CaCO_3$, CaO, $CaSO_4 . \frac{1}{2}H_2O$, $CaSO_4 . 2H_2O$ $3Ca_3(PO_4)_2 . CaF_2$, CaF_2	215
PO_4^{2-}	H_3PO_4, $Ca_3(PO_4)_2 . CaF_2$	3
SO_4^{2-}	H_2SO_4, $(NH_4)_2 Fe_6(SO_4)_4 (OH)_{12}$, $CaSO_4 . \frac{1}{2}H_2O$ $CaSO_4 . 2H_2O$, metal-SO_4	55
Al	Al_2O_3, $Al_2(SO_4)_3$, Na_3AlF_6	3.5

is derived from an AlF_3-plant and ~65% from a H_3PO_4-plant (D. N. Z., Fig. 1. 5). The basic chemical processes involved during the production of AlF_3 and H_3PO_4 are illustrated below:

$$3Ca_3(PO_4)_2 . CaF_2 \Longrightarrow HF \Downarrow \boxed{AlF_3} \quad + \quad Al(OH)_3 \quad \text{gypsum (hemihydrate)} \Rightarrow \text{Sörfjorden discharge}$$

$$CaHPO_4 + H_2SO_4 \Longrightarrow \boxed{H_3PO_4} \quad + \quad \text{gypsum (dihydrate)} \Rightarrow \text{Sörfjorden discharge}$$

Gypsum (of 30 to 100 μ grain size) from the H_3PO_4-plant is pumped as a suspension (250 g/l seawater) into the fjord at 8 to 10 m depth. Its discharge from the AlF_3-plant consists of particles of somewhat larger grain size (100-200 μ). Both the suspensions of gypsum have

densities higher than that of seawater (Environmental Committee Report, 1973).

Approximately 400 tons of P is discharged into Sörfjorden every year, of which only 3% resides in untreated sewage. The main P contributions come from the H_3PO_4-plant, P being associated with gypsum effluent.

Of the total discharge of sulphates, ~60% is readily water soluble. The non-soluble fraction comprises various heavy metal sulphates.

PART II

HYDROGRAPHY AND HYDROCHEMISTRY

CHAPTER 3

HYDROGRAPHY AND NUTRIENTS

Estuaries can be classified from their hydrography (stratification or salinity distributions) into four main types: highly stratified (salt wedge), fjords, partially mixed and homogeneous (Pritchard, 1955; Cameron and Pritchard, 1963). Fjords situated in Canada (Pickard, 1961), New Zealand (Garner, 1964), Chile (Pickard, 1971) and Norway (Saelen, 1967) are all characterized, at least at certain times of the year, by a high density stratification and an estuarine circulation in the upper waters (Pickard, 1961, p. 923), regardless of the differences of such factors as river runoff, tides, sill depths, wind, etc.

The distribution of dissolved oxygen and nutrients in various fjords also shows many similarities. Some fjords display a midwater oxygen minimum (Thompson and Barkey, 1938; Pickard, 1961; Gade, 1973). Others are characterized by oxygen deficiency in the bottom water (Strøm, 1936; Anderson and Devol, 1973). The distribution of nutrients in several fjords may be inversely related to the oxygen distribution and is likely to be the result of organic matter breakdown (Reid, 1965). Alternatively, their distribution in other fjords may be controlled by a water advection through estuarine circulation (Ketchum, 1967; Stumm and Morgan, 1970).

A study of the hydrography of Sörfjorden was undertaken

to obtain some general information on the circulation, particularly of its upper waters (< 100 m), so that the dispersal of pollutants in different water bodies could be better understood. Three cruises were arranged at different seasons, but during separate years (August 1972, September/October 1973 and April 1974), to evaluate the influence of varying riverwater discharge on the hydrographical structure of the fjord. It was also intended that such data would demonstrate both seasonal and areal variations in the extent of mixing, as a two-layer flow was indicated in the upper 20-30 m; a phenomenon seen in other fjords (Rattray, 1967).

Some attempts will be made to assess the limits of water volumes participating in the flow pattern in spite of the fact that simultaneous current measurements were not made. As the tidal amplitude in Sörfjorden is small (<1 m, Table 1.1), the effect of tides on circulation has not been assessed.

3.1. Results

Salinity (‰) and temperature (^{o}C) records for the uppermost 95 m of water profiles at stations shown in Fig. 3.1 (and Table A 2, Appendix A), were made using a N.I.O. temperature-salinity bridge limited to a 95 m depth (Appendix A). Dissolved oxygen (ml/l) and dissolved phosphate and silicate (μg-at/l) measurements (Appendix B) have also been made for the same stations, but include in addition to shallow water data information on the mid- and deep waters of the fjord. The data are presented in Table D 1, Appendix D and station logs in Table A 2, Appendix A.

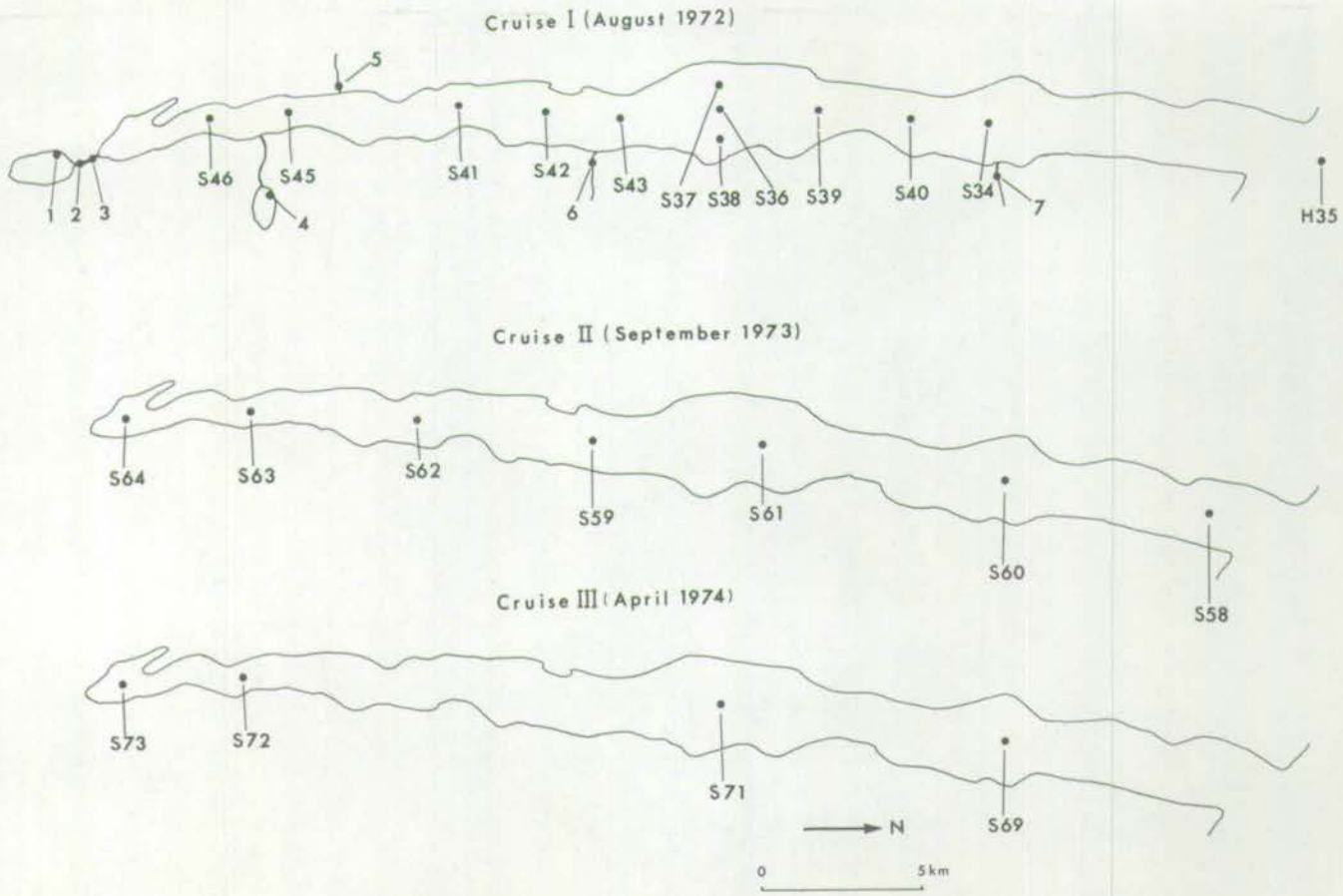


Fig. 3.1. Location of water collecting and/or hydrographic stations in Sörfjorden (see Table A 2, Appendix A for station logs).

By regarding both S and T as a conservative property of waters, especially below the halocline, T-S diagrams have been drawn to identify water bodies of different origin. The vertical extent of the surface flow and the depths of no-net-motion at different times of sampling have been determined following the method of Tully (1949) (see below).

3.2. Seasonal and areal variations of salinity

As the density (σ_t) of seawater in fjords is mainly governed by salinity (S), small changes in S will influence the dynamic balance of various watermasses. With evaporation at a minimum, such changes are brought about almost exclusively by the mixing of freshwater and seawater initially at shallow depths. Hence, S (and σ_t) of the upper waters is directly dependent on the level of freshwater input and its ability to mix with water of greater S. Table 3.1 shows that the seasonal change in S, due to variable

Table 3.1. Maximum annual changes of salinity and temperature in Sörfjorden at various depths (after Svendsen, 1973)

Depth (m)	Smax ‰	Smin ‰	ΔS	Tmax °C	Tmin °C	ΔT
0	32.929	5.799	27.130	14.55	2.57	11.98
20	33.697	30.224	3.473	9.77	3.83	5.94
50	34.500	33.281	1.219	7.57	5.41	2.16
75	34.755	33.854	0.901	7.46	6.51	0.95
300	35.005	34.944	0.061	6.60	6.58	0.02

dilution by introduced riverwater is confined to the uppermost 50-100 m of water in Sörfjorden. Observations of S in waters in fjords of British Columbia are similar. For instance, Pickard (1961) showed

that the seasonal variation in S is confined within the uppermost 50 m of fjord waters.

With runoff high, as was found during August 1972, a well defined, homogenous upper zone of S is developed, deepening to 10 m towards the head of the fjord (Fig. 3.2). When runoff is less, as occurred during September 1973 and April 1974, this upper zone is restricted to the uppermost 2 m or less of water and the halocline essentially occurs at the surface of the fjord (Fig. 3.2). At these times the position of the halocline deepens slightly seawards, particularly in April 1974, but is never deeper than 5 m. Above the halocline, the S of the surface waters generally increases northwards towards the mouth of the fjord, implying that some entrainment of salt occurs. However, in September 1973 the S at depths between 1 and 4 m increased southwards (Table D 1, Appendix D). This unusual feature is related to a progressive shallow inflow of warm, less saline water and will be discussed in 3.7.

Waters underlaying the halocline (the lower zone; Tully, 1949) display much less seasonal and areal variations. However, during periods of high runoff (e.g. August, 1972) the S profiles below the halocline show a persistent, positive gradient with depth, implying some freshwater transport from the upper zone. This is best illustrated at southern stations, for instance S 46, where a deepening of the halocline is observed (Fig. 3.2).

Hydrographical measurements in April 1974 purposely undertaken before the melting of winter snow, suggest considerable upward mixing of salt into the surface layer (S = 9.6-31.2‰).

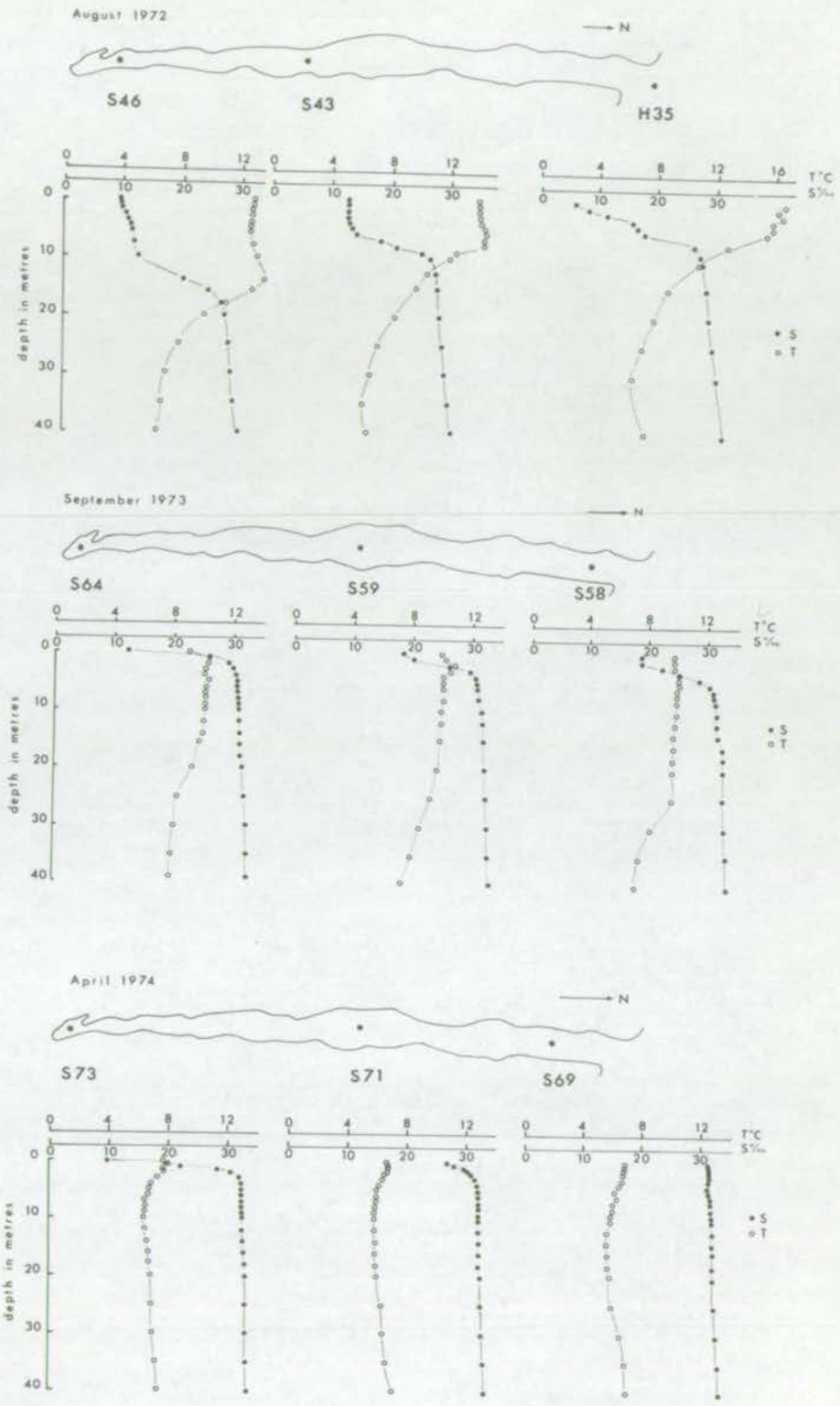


Fig. 3. 2. Depth profiles of S and T during high runoff, August 1972, medium runoff, September 1973, and low runoff, April 1974.

It would appear that low runoff creates weak stratification which consequently facilitates mixing between riverwater and seawater.

3.3. Seasonal and areal variations of temperature

In contrast to salinity, variations in water temperature (T) are relatively unimportant as a control of density stratification in fjord waters. Hence, the halocline corresponds to the pycnocline; the former term will be used in this text in reference to the density boundary. Only when waters are essentially isohaline will changes in T have any significant influence on the stability of various watermasses.

The T profiles of Fig. 3.2 show most clearly a pattern that relates to season. In August and September the surface T values are higher than at depth, while the opposite is observed in April. The T of waters below 70 m appears not to vary significantly with season and ranges between 6.6 and 7.6 in Sörfjorden (Table D 1, Appendix D). The variations of T especially in these upper waters are indicators of variable heat transfer. However, within Sörfjorden it is difficult to differentiate between T changes due truly to solar heating at the surface (see Pickard, 1963) and those caused by inflows of water originating outside the fjord. Svendsen (1973) has shown that whereas in extremely cold winters cooling of the upper waters may extend to 100 m, normally it only affects the uppermost 50 m of Sörfjorden.

The position of the thermocline approximates that of the halocline at all seasons; T maxima occur close to the boundary

between the halocline and the lower zone (Fig. 3.2). Below the halocline, the T of water increases southwards in April, probably due to the presence of a cold compensating current, which will be discussed below (3.6). In September the opposite situation occurs, that is the T of water between 2 m and 20 m relates to a warm water inflow (p. 33).

3.4. Seasonal and areal variations of dissolved oxygen

Unlike S and T measurements the determination of oxygen (O_2) was not confined to the uppermost 100 m of water profiles. Nevertheless, variations in O_2 which directly relate to season are likely to be confined to the upper waters. In contrast the temporal change in O_2 saturation at depth (e.g. >100 m) represents only an indirect expression of seasonal control on deep water movements. Profiles of dissolved O_2 at stations situated in the middle of the fjord in 1972, 1973 and 1974 are given in Fig. 3.3. Data in Table D 1, Appendix D show that the waters of Sörfjorden are oxygenated at all depths. The lowest concentration (2.27 ml/l O_2) occurs in the near bottom waters in the south (S 72). Within the upper waters ($\lesssim$ 50 m) O_2 concentrations always exceed 5 ml/l (Fig. 3.3) and show a general upward increase towards the surface where waters are close to being fully saturated. Such a trend is largely due to the combined effect of turbulent mixing with atmospheric O_2 in the upper water layer and a euphotic zone which is generally confined to the upper 25 or 30 m (Braarud et al., 1974). The upper part of the O_2 profiles of Fig. 3.3 reflect the situation in oceans, where the observed vertical and horizontal distribution is the result of an interplay between

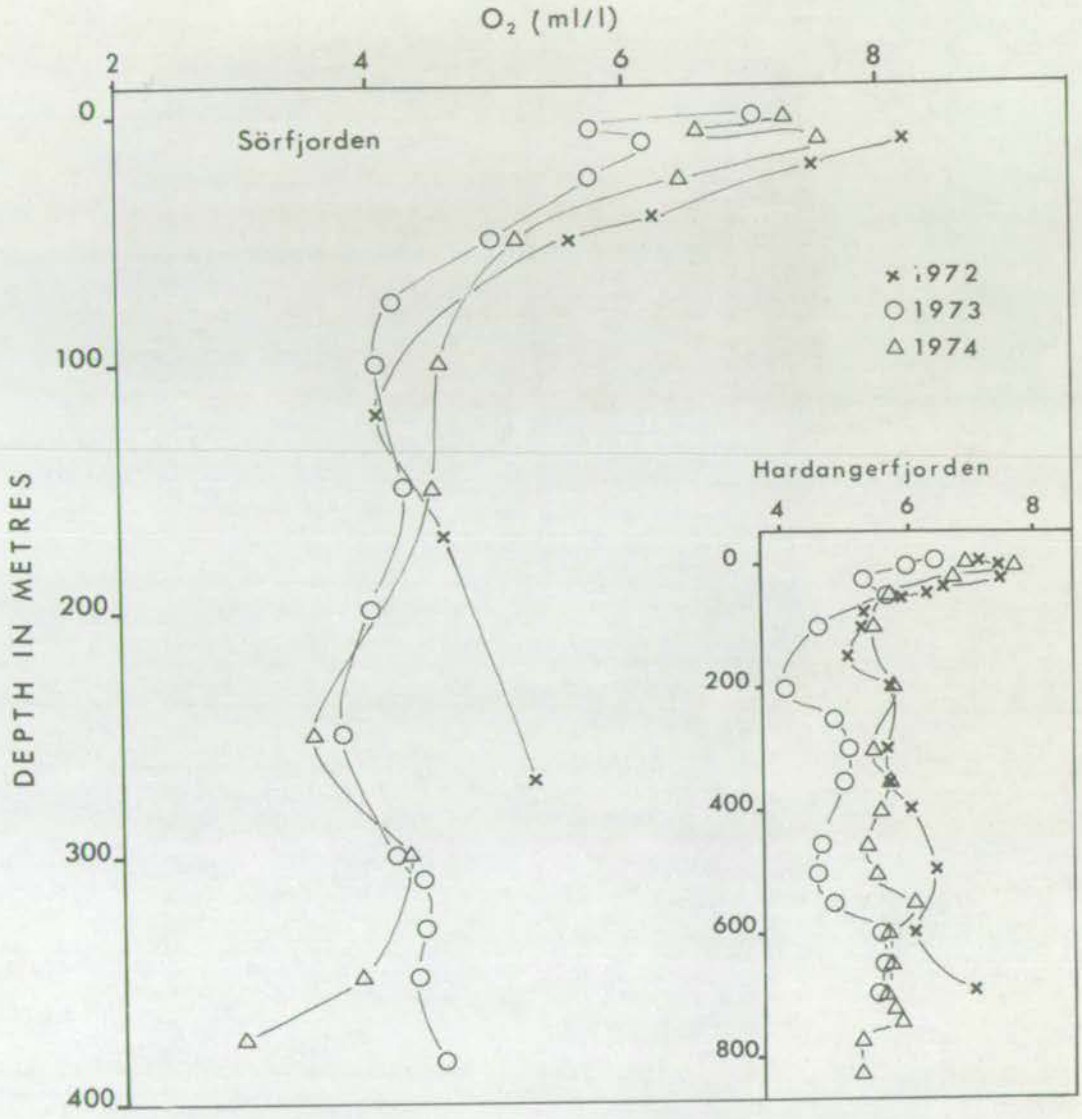


Fig. 3.3. Depth profiles of dissolved oxygen in the middle parts of Sörfjorden and Hardangerfjorden at various years of sampling (data from 1972 after Svendsen, pers. comm.).

biochemical processes e.g. photosynthesis and those by which atmospheric O_2 enters and is transported with the water (Riley and Chester, 1971).

A body of lower oxygenated water exists between 100 and 200 m. It was particularly prominent in September 1973 (Fig. 3.3), and was observed throughout 1972 by Svendsen (1973) (Fig. 3.4). The occurrence of low oxygenated water at midwater depths in fjords, as well as in the open ocean, is well-known (Thompson and Barkey, 1938; Pickard, 1961; Reid, 1965; Gade, 1973). It appears that this minimum is related to biochemical processes and/or to vertical displacement of O_2-poor deep water. Measurements of titration alkalinity were made at a few stations (Appendix B) and they were consistently showing higher values (2.2-2.4) at depths between 100 and 200 m; coinciding with the O_2 minimum. This suggests that the increase in alkalinity in these waters is due to an increase in carbonate alkalinity as a result of oxidation of organic matter.

In the basin waters (> 250 m) considerable seasonal variations are evident (Fig. 3.3); these are related to periods of flushing (discussed in 3.8).

The areal distribution of dissolved O_2 in the fjord shows a general northerly increase at all depths and at all seasons (e.g. Fig. 3.5). This trend is likely to be associated with lateral differences in the stability of the water and the rate of water exchange. A seaward decrease of the stability facilitates greater vertical mixing and, as a consequence, a downward transport of dissolved oxygen. Near the mouth of the fjord a free exchange of water from Sörfjorden

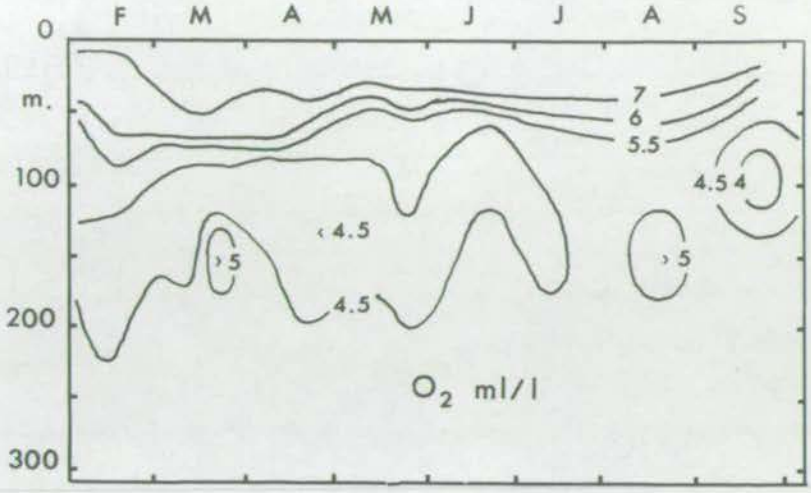


Fig. 3.4.

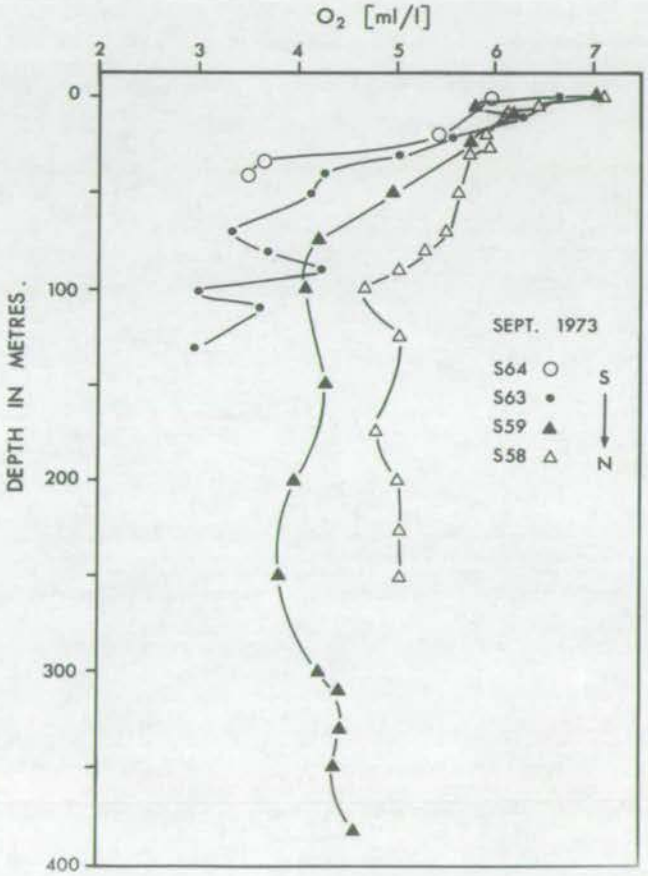


Fig. 3.5.

Fig. 3.4. Distribution of dissolved oxygen in the middle of Sörfjorden during 1972 (after Svendsen, 1973). (top figure)

Fig. 3.5. Areal distribution of dissolved oxygen during September 1973. (bottom figure)

and higher oxygenated water from Hardangerfjorden (Fig. 3.3) can take place above the Hausaneset Sill, raising the O_2 content in the bottom waters of the fjord.

3.5. Seasonal and areal variations of nutrients

The presence of available phosphate (PO_4-P) and silicate (SiO_4-Si) within the euphotic zone of oceans is essential in sustaining biological activity (Redfield, 1955). Their concentrations in deep waters are regulated by regeneration processes (Chow and Mantyla, 1965), their presence there being largely conservative. For this reason both PO_4-P and SiO_4-Si have been useful in interpreting the nature and the movement of deep water masses (Cooper, 1952; Richards, 1958; Chow and Mantyla, 1965; Metcalf, 1969). In the first instance we may assume the nature of PO_4-P and SiO_4-Si concentrations in the deeper waters of Sörfjorden and the adjacent Hardangerfjorden are essentially conservative and hence will be useful in identifying deep water exchange between the two fjords (see 3.8). Unfortunately, the same argument cannot be applied to the surface waters, as it will be shown that there is considerable biological influence on these nutrients. Fig. 3.6 effectively illustrates the low concentrations of both elements in the upper 25 m of fjord waters (see also Table D 1, Appendix D). There is little seasonal variation of PO_4-P within this minimum nutrient zone. In contrast, concentrations of SiO_4-Si are considerably higher in September than at other times (Fig. 3.6). Autumnal increases in SiO_4-Si concentrations in the upper water of the Strait of Georgia have also been observed (Tully and Dodimead, 1957). The reason for this change

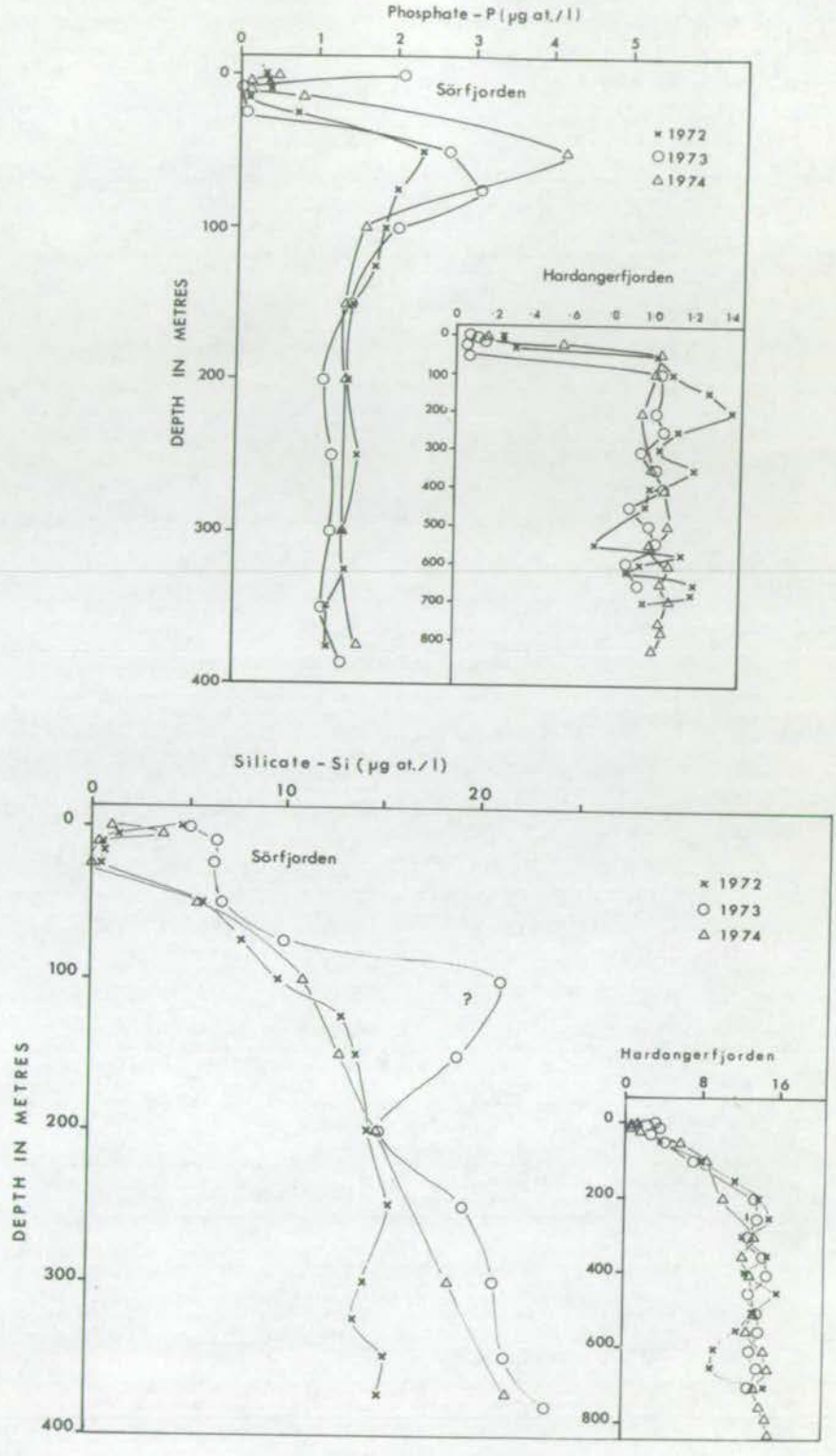


Fig. 3.6. Depth profiles of dissolved phosphate and silicate in Sörfjorden (S 36, S 59 and S 71) and Hardangerfjorden (H 35, H 65 and H 70) during various years of sampling.

is not necessarily related to variations in productivity, but appears to be largely controlled by the plankton composition. For instance, Graham (1941) noticed that the dinoflagellate genus Ceratium, which is abundant in Sörfjorden in autumn, has little demand on the concentration of SiO_4-Si in the water.

The low nutrient zone in Sörfjorden extends vertically to depths close to 25 m (Fig. 3.6); its depletion is confined to the euphotic layer. At greater depths, the PO_4-P distribution does not conform to the SiO_4-Si distribution either in Sörfjorden or in Hardangerfjorden (Fig. 3.6). In Sörfjorden at 50-75 m depth a pronounced maximum of PO_4-P occurs at all seasons, showing extremely high concentrations towards the head of the fjord (Fig. 3.7) (e.g. S 46 - 50 m, 9.02 μg-at PO_4-P/l). Such a trend has been noted by Redfield (1955), Ketchum (1967) and Stumm and Morgan (1970) in fjord-like bodies of water with an upper water estuarine circulation and has been interpreted as being due to trapping of nutrients, consequent to release of nutrients into the compensating current and inward transport. However, in these instances PO_4-P concentrations were much lower (<1 μg-at/l) than those noted in Sörfjorden. Yentch (in Ketchum, 1969) postulated that PO_4-P values in excess of 2.8 μg-at/l represent polluted water. It would follow that the sub-surface water of the inner part of Sörfjorden is polluted. Such an argument can be extended to those waters immediately beneath the compensating current (>25 m) (3.7) for the greater length of the fjord. Further, it would seem from the trend of increasing PO_4-P values to the south, that such contamination is due to industrial discharge about Odda (see Table 2.4).

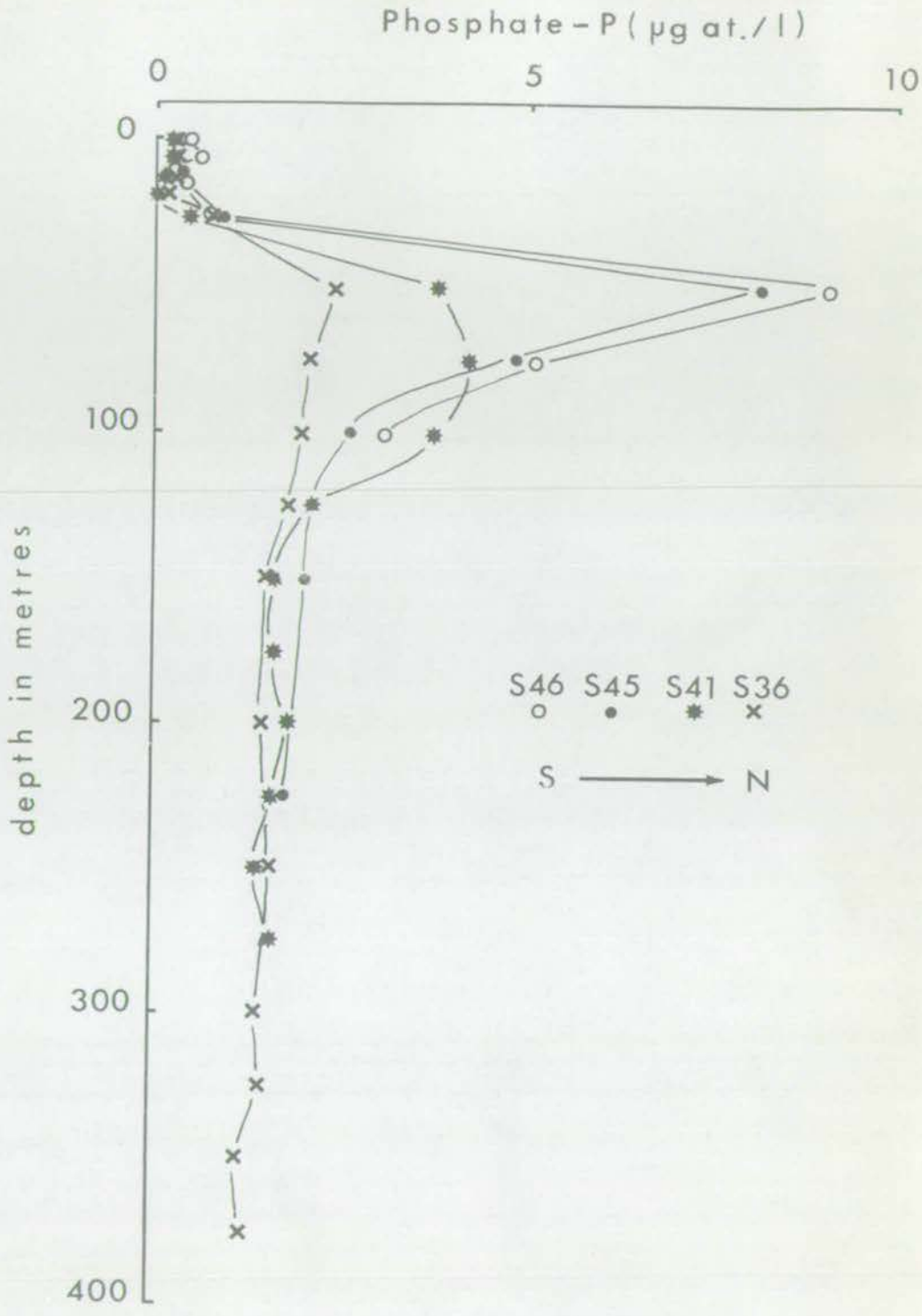


Fig. 3.7. Areal variation of dissolved phosphate during August 1972.

Below 100 m the concentration of PO_4-P is uniform both areally and seasonally and commensurate with values in Hardangerfjorden (1-1.5 μg-at PO_4-P/l) (Fig. 3.6; Table D 1, Appendix D). In contrast, the SiO_4-Si tends to display a more seasonal variation (Fig. 3.6). This discrepancy in the behaviour of PO_4-P and SiO_4-Si in the deeper waters may be due to the difference in behaviour of fallout of organic matter and skeletal remains (Grill and Richards, 1964). That is dissolution of P in organic substances is faster than that of skeletal Si. For instance, Riley (1951) has argued that only some 10% of the original particulate organic matter remains below 200 m in the oceans. Hence its dissolution tends to occur mostly in the uppermost waters and may explain the uniformity in dissolved PO_4-P concentrations in the mid- and deep waters. The steadily increasing concentration of SiO_4-Si towards the bottom (Fig. 3.8) may indicate a persistent release from silica-bearing suspended particulate matter. Alternatively, such a trend may imply release of SiO_4-Si from sediments and its migration into the overlaying waters (cf. Fanning and Schink, 1969). The different behaviour of PO_4-P and SiO_4-Si during decomposition of organic remains in either the water and/or the sediment, may also be reflected in the vertical change of SiO_4-Si/PO_4-P ratios. In Table 3.2 the SiO_4-Si/PO_4-P ratios at station H 70 in Hardangerfjorden, not affected by PO_4-pollution, show an increase from 5.5 at 50 m depth to 15.3 at 825 m. Increases in SiO_4-Si/PO_4-P ratios with depth have also been observed in open ocean water (Chow and Mantyla, 1965) and may be attributed to regeneration processes as cited above.

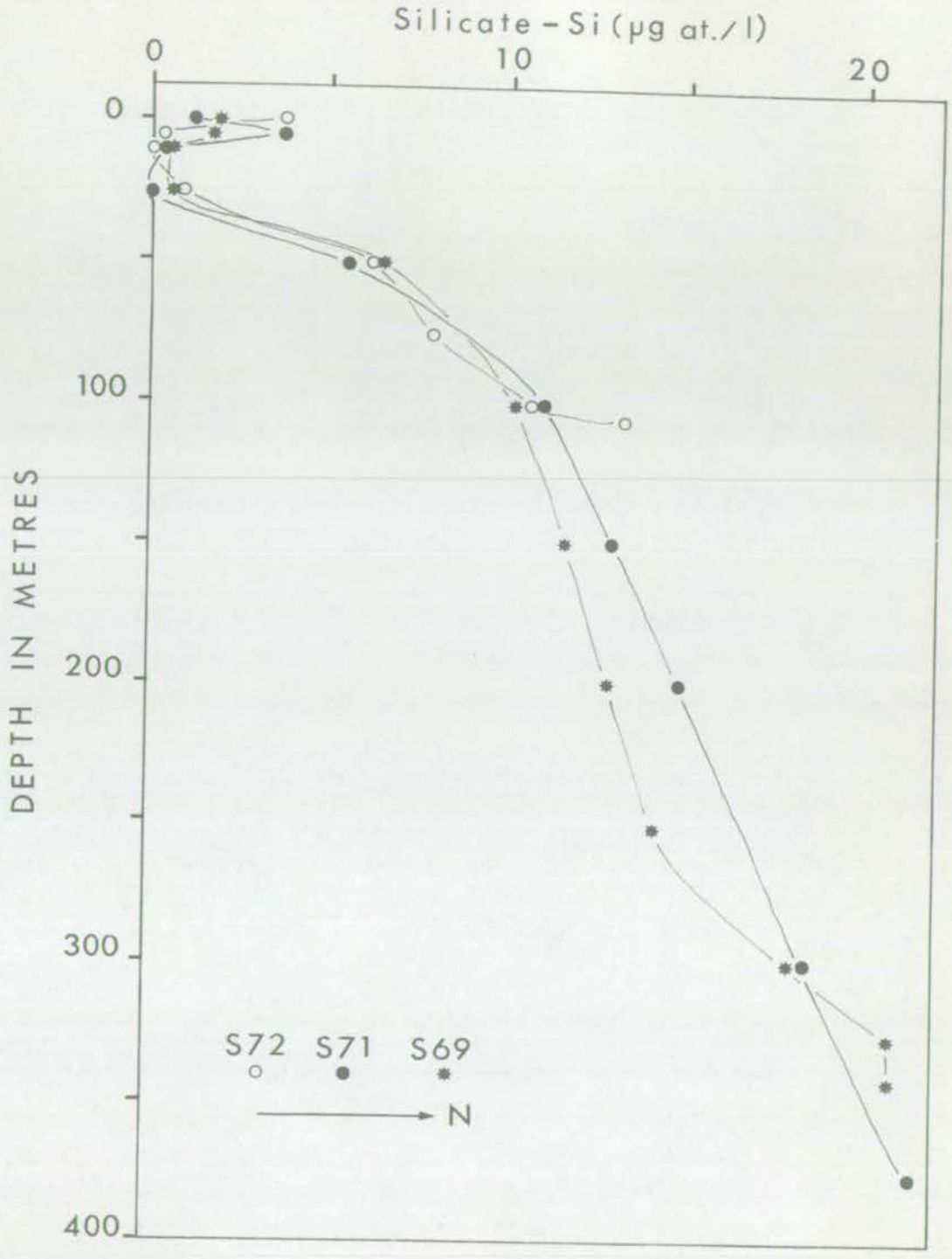


Fig. 3.8. Depth profiles of dissolved silicate for various stations in Sörfjorden during April 1974.

Table 3.2. Dissolved silicate/phosphate ratios in the water of Hardangerfjorden (H 70)

Depth (m)	SiO_4-Si/PO_4-P
0	6.5
5	1.9
10	0.6
25	2.4
50	5.5
100	8.4
200	10.7
300	12.7
350	12.4
400	12.2
500	12.7
550	12.9
600	13.6
650	14.5
700	12.2
750	13.7
775	13.7
825	15.3

3.6. Identification and classification of water types in the upper 100 m of Sørfjorden

Studies on the conservative properties of seawater have enabled water types of different sources to be easily recognized. By definition a conservative property can only be changed by the physical mixing of waters of different origins. Within oceans, the relationships most frequently used to interpret the sources of waters and their transport are T-S (Worthington and Metcalf, 1961), T-Si (Metcalf, 1969) and O_2-S (Rochford, 1958). Their application has mainly been restricted to studies of deep ocean watermasses as the behaviour of some properties (e.g. O_2 and nutrients) becomes non-conservative in shallow water. Here they are influenced not only by the physical processes of advection and diffusion, but also by biological

activity. For this reason, O_2 and nutrients have not been used in classifying watertypes* in the upper waters of Sörfjorden. It has also been pointed out that T is not truly a property of the surface water, due to the heat exchanged between the surface layers and the atmosphere (Tully and Dodimead, 1957). Nevertheless, the physical interrelationship between T and S has been considered as a useful tool in studying seasonal changes in watermass characteristics and circulation in estuaries (Waldichuk, 1957); regarding T below the halocline as a property determined by the T of advected water.

Before considering the watermasses in the upper 100 m in Sörfjorden, it is necessary to identify the different watertypes and the seasonal changes of their characteristics. The water occupying the upper zone will always be referred to as water type A, even if this is not a watertype in accordance with the definition of Pickard (1963) (see footnote). Watertypes at depths greater than the halocline have been identified and classified from T-S diagrams.

a) Cruise I, August 1972.

The surface water (A) is characterized by T higher than 12.5°C and S less than 14‰ (Fig. 3. 9). The same T-S diagram indicates the existence of another watertype (B) of higher S and

---

* The terms watertype and watermass are defined in accordance with Pickard (1963, p. 100).
A watertype is a water body which is represented by a point or usually a small scatter of points in a T-S diagram.
A water body which is represented by points scattered about an ideal line is called a watermass.

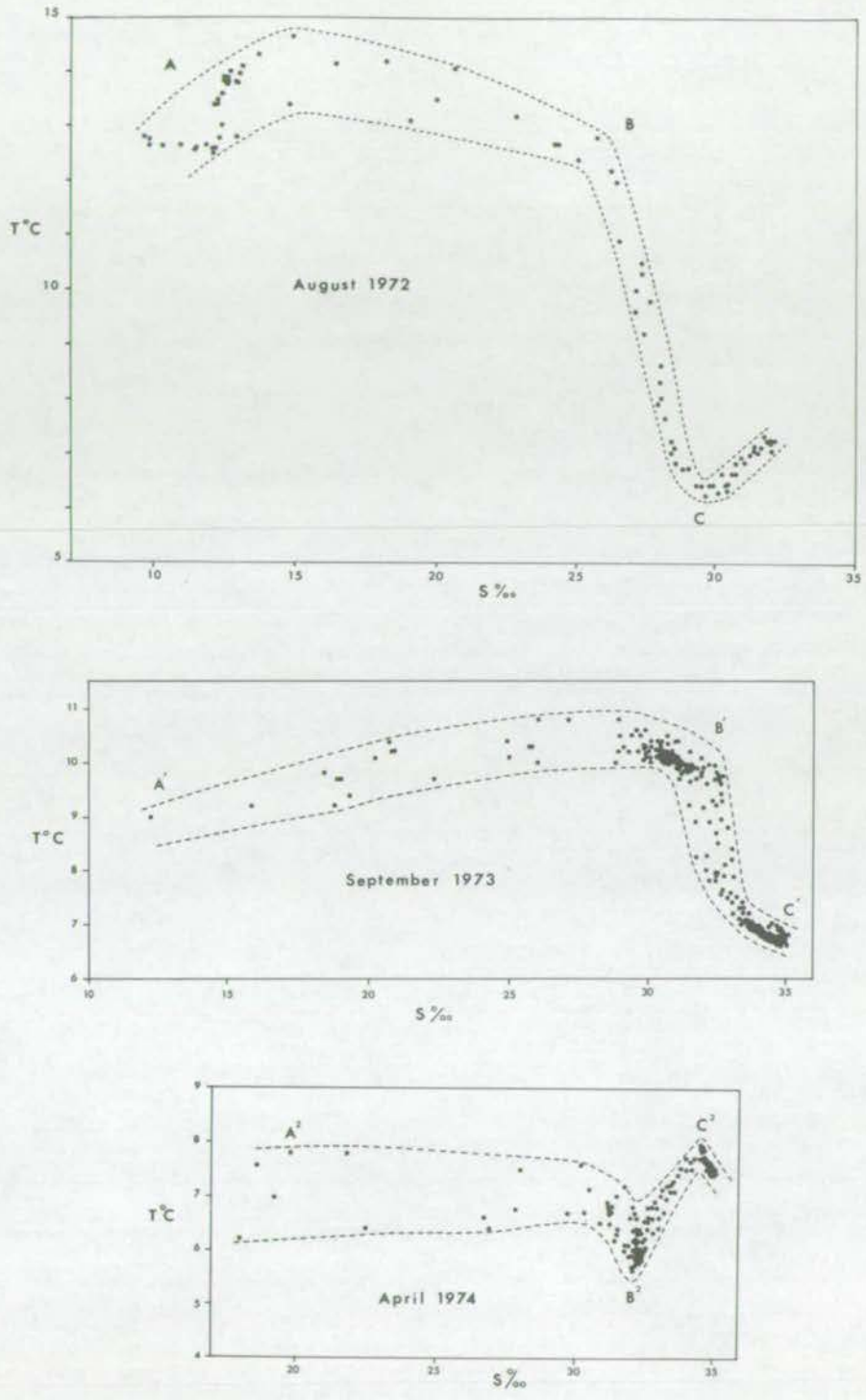


Fig. 3. 9. T-S diagrams of the uppermost 100 m of water collected in Sörfjorden during August 1972, September 1973 and April 1974.

slightly lower T, situated between 15-20 m depth. At 30 and 40 m depth a third watertype (C) is observed, displaying a T-S relationship of T = 6.2 - 6.4°C and S = 29.6 - 30.2‰.

b) Cruise II, September 1973.

The shape and slope of the T-S diagram in September 1973 is quite similar to that seen in August 1972 (Fig. 3.9), although a displacement of T and S is apparent. At 5 to 20 m depth the watertype B^1 shows a T-S relationship of T = 9.9 - 10.4°C and S = 30.0 - 31.5‰, very different from B of Cruise I. Watertype C^1 is recognized by the cluster of points seen at the bottom right of the diagram (Fig. 3.9), representing waters situated close to 100 m depth. It should be noted that watertype C^1 occurs some 50 m deeper than that of C during Cruise I.

c) Cruise III, April 1974.

Data from this cruise again demonstrate three watertypes; A^2 representing surface water (originally riverwater), B^2 sub-surface water (10-15 m depth) and C^2 situated at 50 to 60 m depth and displaying ranges of T = 7.7 - 7.9°C and S = 34.52 - 34.56‰.

During August 1972 and September 1973 watertype B and B^1 display a considerably higher T than B^2 in April 1974. This conforms to seasonal changes in hydrographic conditions in coastal waters. For instance, Svines (1970) has shown that surface waters outside Hardangerfjorden in March (1956) had a T of 2 to 3°C.

3.7. Mixing and movement of watermasses in the upper 100 m in Sørfjorden

Watermasses result from mixing of two or more water-

types (Pickard, 1963). For instance, in Fig. 3.9 watertype A, which originally consists of riverwater, mixes with watertype B to form the watermass AB.

Characteristically, fjords display an outward flow of surface water, compensated by an inward flowing countercurrent. Current measurements carried out in Sörfjorden (Svendsen, 1973) have revealed this two-layer upper water circulation at all seasons. Hence, we can assume that the watermass AB, the resultant of a mixing of river water and saline water, always has a net outflow. This net outflow will induce a deeper inflow of saline water into the fjord, here recognized as watermass ABC; that is the compensating current constitutes watertype B which mixes with water above (A) and below (C).

The mixing of fresh and saline water can result from diffusion and/or entrainment (Carstens, 1970). The relative importance of these two mechanisms depends largely on the turbulence within the two water layers. For example, if turbulence is equal in the surface fresh layer and underlaying saline layer, no net entrainment will occur and vertical mixing occurs through eddy diffusion. Carstens (1970), who studied the upward saltflux into the surface layer of Frierfjord, South Norway, made estimates of the entrainment/diffusion ratios and found that they varied between 0.1 and 5.4. He also observed that the entrainment could vary between 40 to 150% of the river runoff. Saelen (1967) claims that for the larger Norwegian fjords the surface outflow of low-salinity water will be between 2 and 6 times as large as the freshwater supply.

Unfortunately, the limited hydrographical data for Sörfjorden are insufficient to allow a detailed investigation into the mixing processes, which will be of considerable importance when the chemistry of dissolved and particulate elements is considered. However, it is evident from Fig. 3.2 that the surface S at high runoff does not vary much from the head to the mouth of the fjord. In contrast, when runoff is at a minimum (April 1974) there is a conspicuous increase in seaward S. This may imply that entrainment is small relative to river discharge during high runoff and high during low runoff, although the net entrainment is greater during periods of high river discharge than at low. This is in good agreement with Waldichuk's (1957) observations in the Strait of Georgia, British Columbia. It appears that as runoff increases the system becomes more stratified and the entrainment of seawater in the upper layer is obstructed. Accordingly, as one might expect, the ability of the system to rid itself of freshwater is better during high runoff.

Without simultaneous current-measurements, an indirect technique of evaluating the vertical extent of the surface flow (AB) and the depth of no-net-motion must be sought. The closest approximation to that from direct hydrographical measurements appears in the technique used by Tully (1949). Following Tully's method and plotting S against log depth in Sörfjorden, three well-defined zones appear as straight lines of constant slope. That is, an upper zone, the halocline and a lower zone (Fig. 3.10). The break in the S-depth profile between the halocline and the lower zone is taken, following

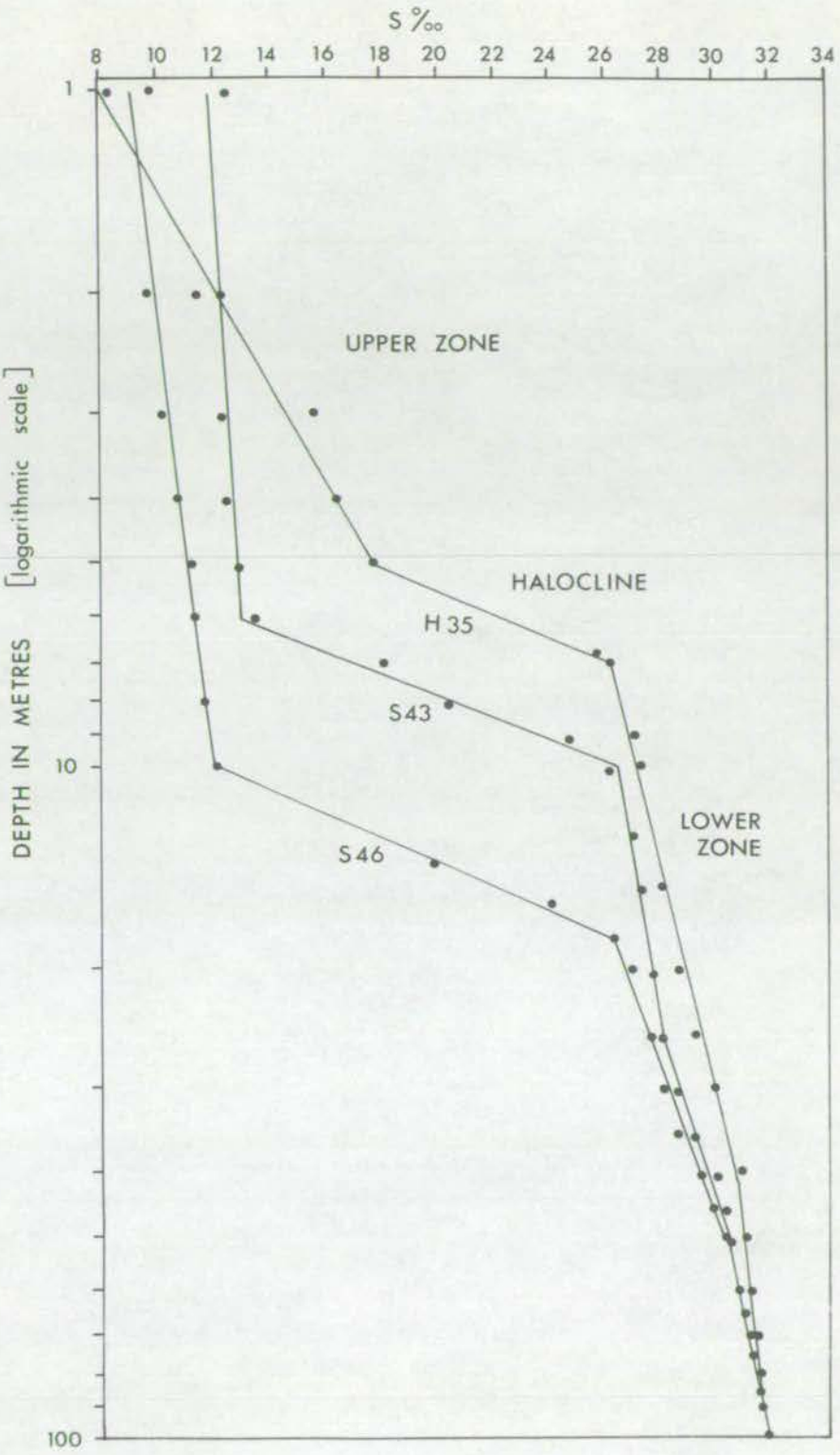


Fig. 3.10. Salinity profiles for stations H 35, S 43 and S 46 during high runoff, August 1972, (note depths are plotted on a logarithmic scale).

Tully (op. cit.), as the depth of no-net-motion and consequently the maximum vertical extent of the surface flow (AB). This technique has been used successfully in several studies of deep estuaries, where freshwater input exceeds evaporation (Tully, 1949; Pickard and Trites, 1957; Tabata and Pickard, 1957). Unfortunately, Tully's method seems less applicable in situations where runoff is low and where the halocline almost extends to the surface. Hence, the assessment of the S-log depth plot for data for April 1974 is expected to be less accurate than the plots shown in Fig. 3.10.

In August 1972 the surface of no-net-motion is situated some 18 m below the sea surface in the south (S 46) becoming shallower northwards (S 43, Fig. 3.10). It conforms closely to a line of σ_t = 20 or S = 26.5‰ (Table D 1, Appendix D). The constancy of S at this boundary has also been observed by Tully (1958) who used it to confirm that the surface of no-net-motion is a surface of unidirectional upward transfer. Presumably, during other cruises, while there exists a strong velocity shear at 1 to 2 m, the outflow may extend some 5 to 10 m below the surface (Rattray, 1967), deepening somewhat seawards.

With entrainment, net seaward transport must increase towards the mouth of Sørfjorden, although the thickness of the outflowing watermass (AB) does not necessarily have to increase. Normally the surface layer becomes more saline seawards and its velocity as a consequence increases (Pickard and Trites, 1957).

The two-layer estuarine circulation induced by river runoff is comprised of a seaward surface flow of watermass AB and

watermass ABC; it acts an an opposite directed compensating current, and has been up to date, for the sake of simplicity, considered isolated with respect to deep water movements. However, the origin of water type C and the movement of watermass BCX, where X is an assumed watertype situated beyond depth of sampling, is less clear. Pickard and Rodgers (1959) observed in inlets of British Columbia a two-layer circulation confined to the uppermost 50 m, and a well developed seaward flow at 100 m; the origin of the latter current was unexplained. However, McAlister et al. (1959), in their study of Alaskan fjords, have suggested that during periods of high runoff more water entered the fjord in the compensating inflow than was transported out at the surface. Hence, they invoked a small outflow at greater depths, implying that surface currents cannot always be considered in isolation with respect to deep water movements. Carstens (1970) has also indicated that circulation in most deep fjords is in reality a system of superposed layers with alternating flow directions from surface to bottom.

The lack of hydrographic measurements below 100 m in Sörfjorden makes any assessment of the deep water flow very difficult. However, the interpretation of data collected on water chemistry suggests that waters underlaying the compensating current have a net outflow. This feature will be discussed in detail in the following chapters.

Hydrographic data from September 1973 (Cruise II) indicate unusual conditions in the upper waters. Unlike conditions observed in other seasons, S in the near surface waters increases

southwards (p. 19). For instance, at 2 m depth S is raised from 23.3‰ near the entrance of Sörfjorden (S 58) to 29.1‰ close to the head (S64). Moreover, the T of the sub-surface water increased significantly during the duration of the cruise. For example, at 40 m depth T was 2.5°C higher at station S 60 than at the same depth of station S 58 (see Fig. 3.1), measured two days earlier (Table D 1, Appendix D). The only plausible explanation accounting for these changes can be a southerly advective flow of warm and less saline water along Sörfjorden. During its southward flow it appears to incorporate or mix with more saline waters; shown by the increase of S towards the head of the fjord. Shallow autumnal inflows of warm, low S water have been previously described in Sörfjorden (Svines, 1970, Fig. 3.11) and other norwegian fjords (Gade, 1973), and are considered to be an annual event. Such inflows are a consequence of a decreasing stability of the watermasses outside the fjord, due to a lessened influence of land runoff. As a result, vertical mixing is promoted and heat is transferred to greater depths than in the more stratified waters within Sörfjorden. This results in the formation of a watermass outside, less dense than the sub-surface water inside the fjord. As a result an exchange of waters is promoted, the resident near-surface fjord water sinks beneath the inflowing water (see p. 38).

3.8. Deep water movements

With the lack of hydrography data below 100 m we have to resort to an interpretation of previously published data of S and T in Sörfjorden and Hardangerfjorden (Saelen, 1962, 1967; Svendsen, 1973)

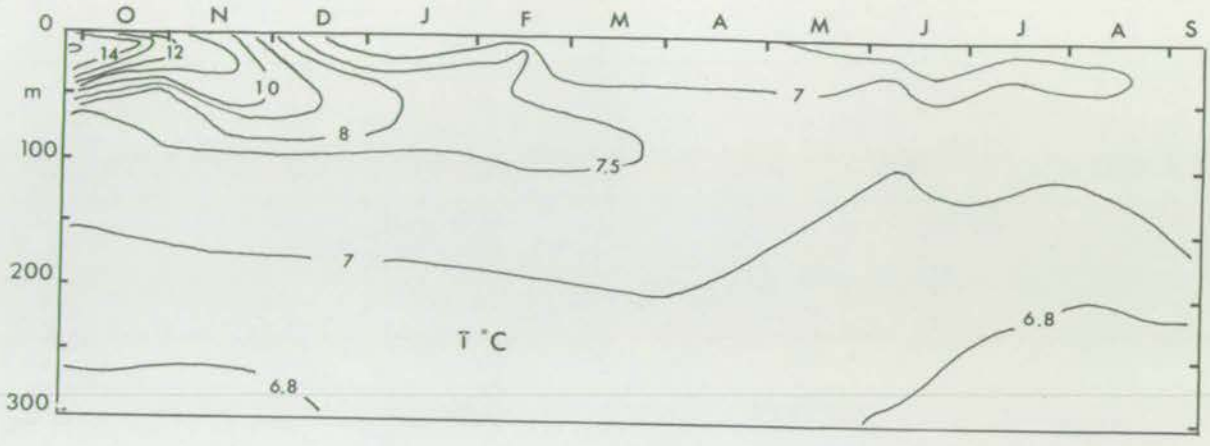


Fig. 3.11. Distribution of temperature in the water near the entrance of Sörfjorden during 1955-56 (after Svines, 1970).

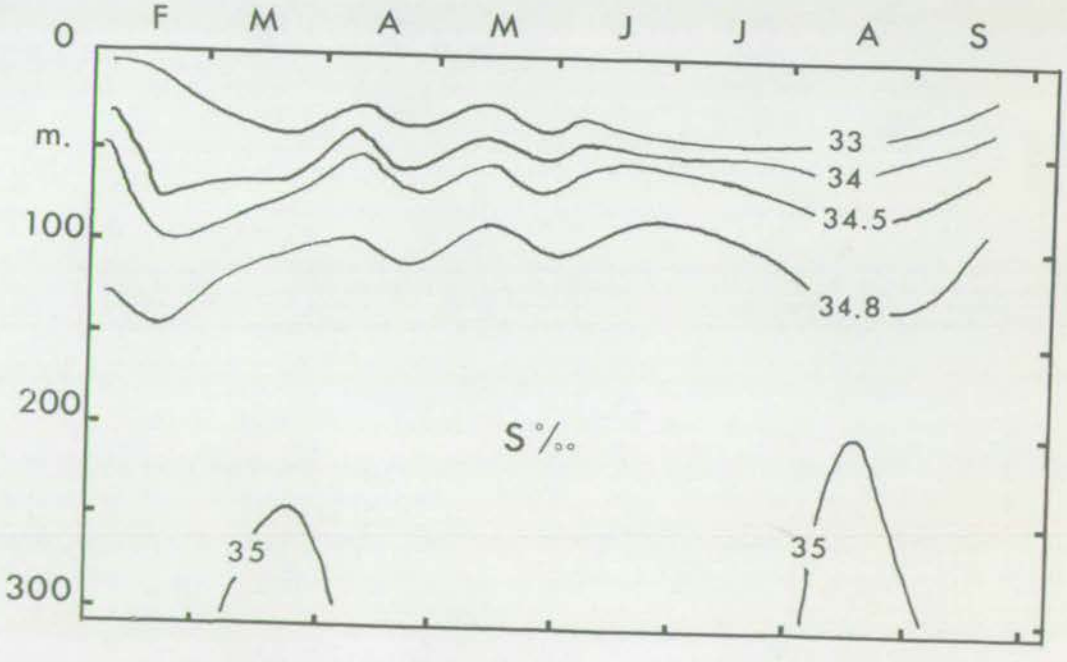


Fig. 3.12. Distribution of salinity near the entrance of Sörfjorden during 1972 (after Svines, 1973).

and O_2, PO_4-P and SiO_4-Si data collected on the various cruises (Table D 1, Appendix D), to gain an understanding of the deep water movements of the fjord. Variations in hydrography and hydrochemistry of fjord water below sill depth can be regarded as the result of an in situ process, comprising interaction between the deeper waters, overlaying waters and/or bottom sediments. S and T may undergo a change through eddy diffusion, reducing the density of the bottom water (Gade, 1973b). Dissolved O_2 may be consumed by oxygen-demanding constituents, principally in the sediment, leading to O_2 deficiency near the seabed (Ström, 1936). The increase of nutrients in the many bottom waters may be interpreted as resolution of biogenic matter at the sediment surface (Tully and Dodimead, 1957; Richards, 1958). Unlike the upper waters there is no obvious seasonal variation in S and T in waters below 100 m (Svendsen, 1973, Table 3.1). It would appear that under normal circumstances hydrographic changes in the lower waters are slow, as has been noted in similar fjord basins (Gade, 1973b). Only when there is physical replacement of the bottom waters, for instance by advective flushing, will any significant change occur. In any case, only by this mechanism can S of the bottom water increase (Pickard, 1961). Deep water exchanges in fjords may be seasonal (Anderson and Devol, 1973) or at least may show some regularity (Gade, 1973b). For instance, bottom water renewal occurred in Hardangerfjorden during spring 1956 (Saelen, 1967) and in 1972 three periods of flushing of varying intensity were observed, of which two affected the basin water in Sörfjorden (Svendsen, 1973,

Fig. 3.12). Flushing does not necessarily imply complete renewal of water below sill depth; for instance, Svines (1970) estimated that the flushing which occurred in Hardangerfjorden in 1956 had an influence on 55% of the deep water masses. Price and Skei (1975) regard flushing in Hardangerfjorden to be incomplete, rarely renewing the deepest water. Complete flushing of water below sill depth (250 m) in Sörfjorden, comprising $\sim 7.6 \times 10^8$ m^3 or ~7% of the total volume of the fjord, may also be a rare phenomenon. That partial flushing in Sörfjorden occurs may be seen in the sequential changes in the dissolved O_2 contents of deeper waters (Fig. 3.3). Dissolved O_2 was not measured during August 1972, but data obtained by Svendsen (pers. comm.) a week after the completion of Cruise I, showed concentrations of O_2 exceeding 5 ml/l in the basin water (i.e. >250 m). These concentrations are similar to those measured in Hardangerfjorden at comparable depths (Fig. 3.3). Such levels are considerably higher than those observed in the basin water during September 1973 and April 1974, that is 3.7 to 4.5 ml/l and 3.0 to 4.3 ml/l respectively. Furthermore, the levels of O_2 between 150 and 300 m in Hardangerfjorden were conspicuously higher in April (5.3 - 5.7 ml/l) compared with September (4.0 - 4.9 ml/l). The discrepancy in the O_2 content between the two bodies of water in September and April is also recognized in the nutrient data; that is Sörfjorden bottom water is richer in nutrients when O_2 is low. Both the O_2 and nutrient data (Table D 1, Appendix D) imply a major renewing of the bottom water in Sörfjorden prior to or during August 1972 and this exchange increased S to 35‰ (Svendsen, 1973, Fig. 3.12).

At other times the properties of the basin water are quite different from those of the waters of Hardangerfjorden of comparable depths and imply no contemporary major water exchange. However, the relatively high concentrations of dissolved O_2 present in the bottom water in September 1973 (Fig. 3.3), suggest that bottom flushing is relatively frequent. The profile of O_2 in April 1974 (Fig. 3.3) indicates that while O_2-rich water may have been introduced over the sill, it affected only the upper part of the basin waters. With regard to flushing of bottom water in Sörfjorden it should be emphasized that such events are coupled with periods of flushing in Hardangerfjorden (Svendsen, 1973). Hence, the water renewing the bottom water in Sörfjorden is displaced deep water from Hardangerfjorden of relatively low O_2 content.

Any displaced volume of water, the result of a complete or a partial flushing, must leave the fjord at shallower depths to maintain volume continuity. This has been directly observed in Fensfjorden, West Norway, where Gade (1973a) recognized the displaced resident water, characterized by a distinct O_2 minimum, leaving the fjord at 100 to 150 m depth.

3.9. A summary of the assumed water circulation in Sörfjorden

As the circulation patterns of surface and deep water in the fjord play a most important part in the transporting of pollutants, redistributed sediments and plankton, it is perhaps appropriate to enumerate and comment on their salient features. An outline of the assumed water circulation in Sörfjorden during August 1972, September 1973 and April 1974 respectively is provided

below. At all seasons a four-layer mechanism is assumed with alternating flow directions.

1) August 1972 (high runoff)

Surface outflow is confined to the upper 10 to 18 m, its salinity is laterally uniform. Although entrainment is great, relative to runoff it appears small. A compensating current is induced at depths between 15 and 25 m. The watermass extending from 20 to 150 m depth has been assumed to have a net outflow, based on chemical evidence (p. 96). This watermass constitutes 5.6 x 10^9 m^3 of water which is ~ 57% of the total water volume of Sörfjorden. If the flow in the upper two layers balances (p. 32), the energy necessary to sustain an outflow at midwater depth must be created in the underlaying waters. This could apparently be set up by a major renewing of the bottom water, seen by the distribution of dissolved O_2, SiO_4-Si and the S and T (Svendsen, 1973). The 'old' water by necessity will be vertically displaced. The volume of water occupying the fjord between 150 m and the bottom is less than half of that flowing out immediately above. Inevitably the bottom inflow is more than twice as rapid as the midwater outflow.

2) September 1973 (medium runoff)

Surface flow is restricted to the uppermost 2 to 5 m. Immediately below, an inflow occurs, probably extending vertically to depths of 60 to 70 m near the entrance of the fjord. This inflow does not appear to compensate for entrained salt, but is thought from T-S data to constitute a gravity flow and is formed to eliminate the density difference between sub-surface waters in Sörfjorden and

Hardangerfjorden (3.7). As the inflowing water is lighter than the resident water, the latter water must leave the fjord as an underflow.

Water enters the fjord at sill depth (250 m), but judging from the O_2 distribution, this water only mixes with the upper part of the basin water. The displaced water originating from the inflow at this depth may contribute to the undercurrent formed by the shallow inflow and together form a midwater outflow extending from ~ 50 m to ~200 m depth.

3) April 1974 (minimum runoff)

During this period the seaward flowing surface layer changes its S by a factor of three from south (9.6‰) to north (31.2‰). Due to the low stability of the water entrainment is extensive relative to runoff and the outflow presumably extends to 5 to 10 m depth. A compensating current extending to ~30 m depth or more underlies the surface flow. Hydrography alone does not describe the condition of water between ~30 m and ~125 m. However, the chemistry of the water provides evidence of a net outflow. An increase of O_2 at the upper part of the basin water (> 250 m), suggests an inflow at sill depth and as a consequence creates some outflow at intermediate depths. Deeper water does not appear to participate in any water exchange. As a result of the homogeneity in the watermasses, vertical mixing between the four alternating layers is likely to be greater in April than at other times.

PART III

SEDIMENTS

CHAPTER 4

THE MINERALOGY AND GEOCHEMISTRY OF THE SEDIMENTS

The examination of sediments was largely confined to a longitudinal coring profile in the central parts of Sörfjorden. Thirty-two gravity cores were collected in all. Sixteen of these were collected from the southern area (Fig. 1 in Skei et al., 1972) during April 1971 (Cruise A). The position of cores collected at other cruises is shown in Fig. 4.1 and a complete station log is given in Tables A 1 and A 2, Appendix A. The locations of all cores collected in Sörfjorden are shown in relation to the bottom topography in Fig. 4.2.

The coring technique is described in Appendix A and preparation of sediments in Appendix C.

The sediments collected during cruise A and cruise B were analysed using X-ray fluorescence analysis for the major elements Si, Al, Ti, Fe, Mg, Ca, K, P and Mn (Appendix C). The results of these analyses, uncorrected for seasalt, are given in Table D 2, Appendix D. As expressed they are likely to contain some contribution of Mg, Ca and K from the residual seasalt.

The dried sediments collected during cruise A were also analysed by X-ray fluorescence methods for Ag, Ba, Bi, Cd, Cu, In, Pb, Sb, Sn and Zn (see Skei et al., 1972, Appendix E). The minor element analyses of sediments collected at other times were confined to Cu, Pb and Zn.

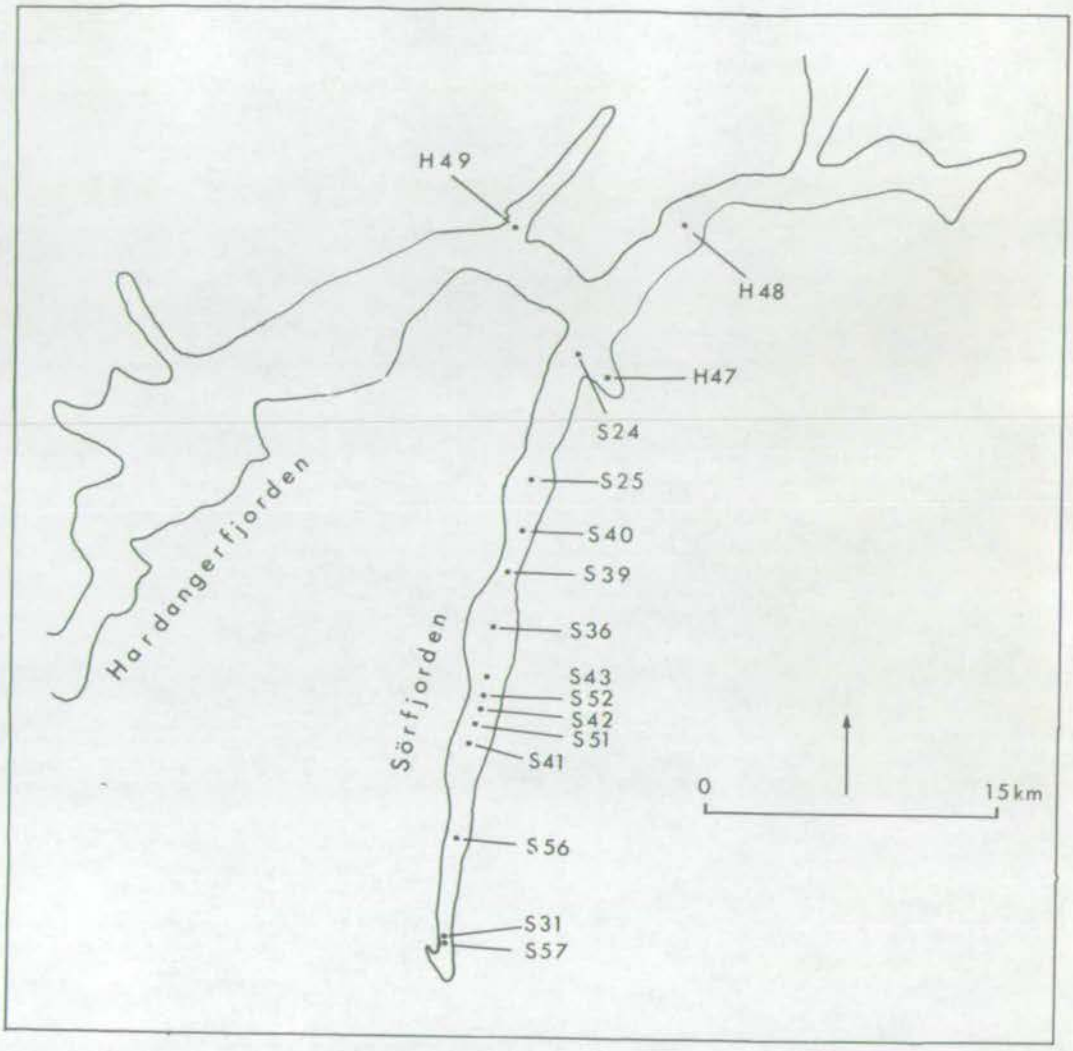


Fig. 4.1. Locations of sediment cores collected during cruise B (1971) and cruise I (1972).

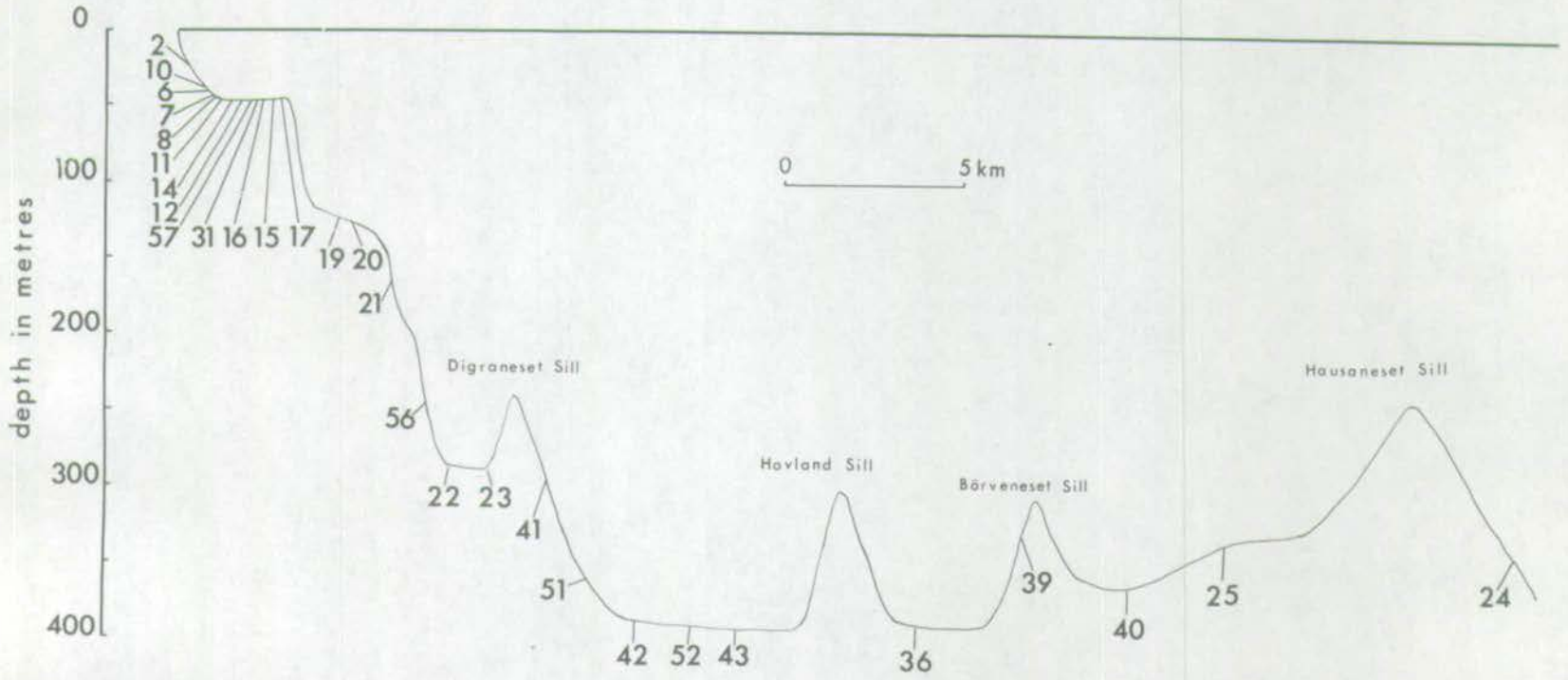


Fig. 4.2. Locations of sediment cores collected in Sörfjorden shown with respect to bottom topography.

Total-C and carbonate-C (core S 25 only) were determined for those sediments collected during cruises A and B. The difference between total-C and carbonate-C measurements provides a measurement of the organic-C of the sediments. The methods are described in Appendix C and the results given in Table D 2, Appendix D.
A mineralogical investigation of some sediment samples was made by using X-ray diffractometry (Appendix C).

4. 1. Colour, texture and grain size

The surface sediments can be sub-divided into two types on the basis of their colour. Surface ($<$10 cm) sediments accumulating south of Digranes Sill (see Fig. 4. 2) exhibit a varying degree of red colouration which is associated with industrial waste. The intensity and thickness of this red colour increase towards core S 57 (not analysed), close to the main discharge point from D.N.Z. (Fig. 1. 5). This core displays throughout its entire length (120 cm) evidence of bright red industrial waste. Generally, in the upper 10 cm of the sediments of the southern area of the fjord, the colours range from red, yellow, brown to black. These sediments, termed 'anomalous' are very different from the sediments north of the Digranes Sill (Fig. 4. 2), characterized by a brown coloured surface, varying in thickness between 3 and 5 cm.

There does not appear to be any seaward trend of decreasing grain size in Sörfjorden as has been noted in other fjords in Norway (Holtedahl, 1965). Most surface sediments are composed of clayey silts and fine sands, although occasionally coarser sediments occur. Within the sub-surface sediments marked changes in colour

and texture are observed. At 15-20 cm depth a dark-coloured layer containing leaves, twigs and coarse sand grains occurs in cores S 42, 52, 43, 36 and 40, all situated in the deepest basins of the fjord. Occasional layers of even coarser sand occur at greater depths. For instance, core S 52 taken in the deepest basin (400 m) shows an increasing grain size below 40 cm, with a gravel horizon occurring at ~55 cm depth. Holtedahl (1965) observed in basin sediments of Hardangerfjorden gravelly and sandy beds at a similar depth (40-60 cm). These were interpreted as turbidite deposits. In Bolstadfjorden, West Norway, Taylor (1974) found coarse sands at the same depth. Similar features observed in the basin sediments of Milford Sound, New Zealand (Pantin, 1964) have been attributed to sediment slumping.

4.2. Mineralogy

Qualitative X-ray diffraction analyses (see Appendix C) on bulk sediment from surface and sub-surface horizons in Sörfjorden and in cores collected outside (H 47-49), show broadly similar diffractograms. Quartz (3.34Å), alkali feldspar (3.24Å), plagioclase feldspar (3.18Å and 4.03Å), illite (10Å), chlorite (7Å and 14Å) and amphibole (8.5Å) appear as the principal minerals. All are common components in the rocks of the drainage area, implying that the bottom deposits are of local origin. Diffractograms of the 'anomalous' sediments (p. 41), besides displaying those minerals listed above, show much calcite (3.03Å) and crystalline compounds not usually found in marine sediments. The intensity of the 3.03Å calcite peak increases southwards and reaches its maximum in core S 2, implying an increasing dilution of detrital alumino-silicates and quartz in this

direction.

In the surface sediments of the harbour area of Odda, zinc-ferrate ($ZnO.Fe_2O_3$) displaying reflections at 2.5Å, 1.5Å and ~3Å, and hematite (α-Fe_2O_3) displaying peaks at 2.7Å, 1.7Å and 2.5Å have been recognized. Many other reflections occur, but unfortunately cannot be attributed with any certainty to other phases likely to be present in these sediments. The mineral jarosite was particularly looked for but not found (see 2.1). This is probably due to the fact that jarosite only has been introduced into the fjord since 1968 (Environmental Committee Report, 1973).

The occurrence of calcite, zinc-ferrate and hematite in the surface sediments almost certainly is due to industrial discharge from Odda (Table 2.3-4).

4.3. Geochemistry of the major elements

Analyses of major elements in the bulk sediments were primarily conducted for a comparison to be made with the analyses of suspended particulate matter in the overlaying waters (see Chapter 5). It was also hoped that their results would give some insight into the influence that industrial discharge (Fe-, Ca- and P-compounds) into the fjord has on the overall chemistry of various sediments.

In order to establish the 'normal' or natural composition of the sediments from Sörfjorden, core S 25 from the northern extremity of the fjord was analysed in vertical profile for Si, Al, Ti, Fe, Mg, Ca, K, P, Mn, total-C and inorganic-C. Table D 2 (Appendix D) shows that these sediments do not show any obvious surface element enrichment, unlike sediments from the southern

part of the fjord.

The chemical characteristics of the Sörfjorden sub-surface sediments compare favourably with other Norwegian fjord sediments which have not been subjected to industrial contamination (Table 4.1). In contrast, the surface 'anomalous' sediments display appreciably more Ca, Fe and P. Further, Tables 4.1-2 show that Ca, Fe and P are the only elements that can be regarded as 'anomalous'. Hence, the Si, Al, Ti, Mg and K contents in these sediments are considered normal, i.e. largely derived from natural runoff, and can be compared with sediment analyses from other parts of the fjord.

a) The geochemistry of Si, Al, Ti, Mg and K.

The values shown in Tables 4.1-2 indicate that concentrations of Si, Al, Ti, Mg and K in Sörfjorden can be explained as a consequence of normal input. All are likely to be associated within detrital alumino-silicates, being components of feldspars and clays. The strong inter-element relationship between them, especially in the surface sediments, is demonstrated by the plots of Si, Ti and K against Al (Fig. 4.3). However, the composition of sub-surface sediments (>10 cm) often shows higher Si, Ti and K with respect to Al and may imply changes in mineralogy and hence grain size (p. 42), between surface and sub-surface samples. It is unlikely that an early diagenetic modification of the clays, such as Al-substitution (cf. Hirst, 1962) would produce such marked variations. In addition, the input of Al as industrial waste (2.3) is unlikely to appreciably alter the relationship of elements to Al to

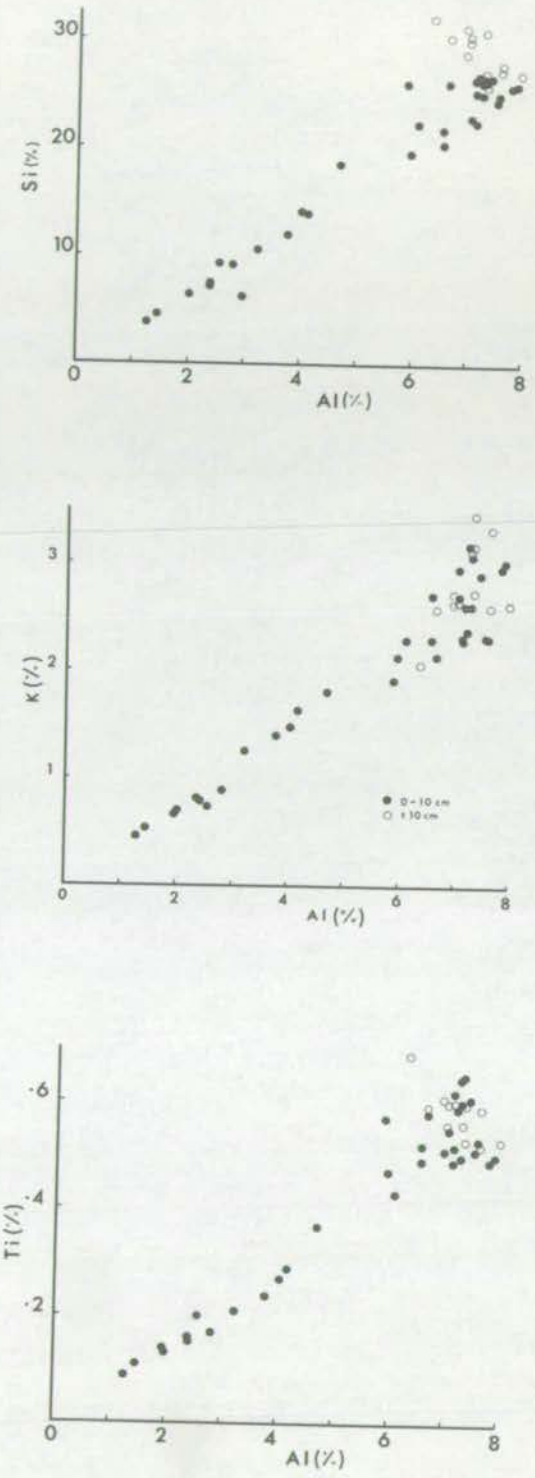


Fig. 4.3. Si-, K- and Ti/Al relationships in sediments from Sörfjorden.

Table 4.1. Major element concentrations in sediments from Sörfjorden and comparable sediments (wt.%)

	1	2	3	4	5
Ca	6.97 0.79-22.18	2.80 0.57-13.63	2.15 1.84-2.40	3.24 2.72-4.32	1.69 -
K	1.53 0.45-2.66	2.24 0.66-3.13	2.72 2.31-3.33	2.91 2.77-3.08	4.15 -
Fe	12.86 5.34-34.51	10.91 4.13-32.07	5.65 4.88-6.90	4.63 3.84-5.17	7.90 -
Ti	0.33 0.09-0.58	0.48 0.13-0.69	0.56 0.49-0.61	0.48 0.44-0.52	0.53 -
Si	15.14 3.72-26.21	21.68 6.23-32.04	27.79 23.39-31.30	25.48 23.57-27.19	24.21 -
Al	4.31 1.26-7.16	5.88 1.97-7.42	7.32 6.67-7.99	6.59 7.04-7.88	8.73 -
Mg	1.05 0.27-2.30	1.45 0.43-2.09	1.69 0.80-2.47	1.42 1.18-1.79	2.40 -
P	0.215 0.021-0.711	0.129 0.055-0.332	0.064 0.54-0.100	0.118 0.100-0.144	- -
Mn	0.102 0.040-0.275	0.104 0.074-0.222	0.095 0.076-0.112	0.116 0.039-0.333	0.124 -
total-C	5.06 1.28-11.18	2.13 0.46-10.26	0.89 0.55-1.24	2.63 1.81-3.92	- -

1. Average and range of 15 'anomalous' surface sediments (Sörfjorden)
2. Average and range of 15 'anomalous' sub-surface sediments (Sörfjorden)
3. Average and range of 13 'normal' sediments (core S 25)
4. Average and range of 21 oxic fjord sediments (Taylor, 1974)
5. Average of 85 Norwegian Quaternary clay samples (Roaldset, 1972)

Table 4.2. Major element/Al ratios in sediments from Sörfjorden and other areas

	1	2	3	4	5
Ca/Al	2.04	0.57	0.30	0.42	0.19
	0.28-7.89	0.24-3.39	0.24-0.32	0.38-0.57	-
K/Al	0.36	0.38	0.38	0.39	0.47
	0.28-0.39	0.32-0.44	0.30-0.47	0.36-0.42	-
Fe/Al	5.27	2.71	0.77	0.62	0.90
	0.87-23.38	0.78-16.24	0.68-0.91	0.53-0.69	-
Ti/Al	0.075	0.070	0.076	0.063	0.061
	0.061-0.100	0.062-0.108	0.067-0.089	0.060-0.071	-
Si/Al	3.44	4.09	3.84	3.42	2.77
	2.94-4.44	3.07-5.03	3.25-4.54	3.27-3.59	-
Mg/Al	0.24	0.24	0.23	0.19	0.27
	0.09-0.32	0.16-0.28	0.13-0.34	0.16-0.24	-
Mn/Al	0.032	0.023	0.013	0.016	0.015
	0.013-0.114	0.012-0.092	0.010-0.016	0.006-0.044	-

1. Average and range of 15 'anomalous' surface sediments (Sörfjorden)
2. Average and range of 15 'anomalous' sub-surface sediments (Sörfjorden)
3. Average and range of 13 'normal' sediments (core S 25)
4. Average and range of 21 oxic fjord sediments.
5. Average of 85 Norwegian Quaternary clay samples (Roaldset, 1972)

the degree that is seen in Fig. 4.3.

The Si/Al ratios of the sediments in Sörfjorden are higher than normally observed in alumino-silicate minerals, suggesting that much of the Si occurs as quartz; this is confirmed by X-ray diffraction analyses (4.2). The abundance of biogenous Si in the sediment is unknown.

Ti/Al ratios are slightly higher than those observed in sediments from other fjords (see Table 4.2), and may be related to differences in the composition of the source rocks. Apparently, most of the Ti content of fine grained sediments is associated with the clay minerals, possibly occurring as TiO_2, rather than being structurallyheld within the clay minerals (Chester, 1965). Goldschmidt (1954) observed higher Ti/Al ratios in sand and silts than in clay rich sediments and attributed this to the presence of more Ti-bearing detrital minerals such as sphene and ilmenite in the former sediments. Such a relationship is consistent with the distribution of Ti/Al ratios between surface and sub-surface sediments in Sörfjorden (p. 42).

The change in Si/Al and K/Al ratios as seen in Fig. 4.3 is also consistent with the suggestion of a change in grain size (p. 42). More quartz and feldspar appear to occur in the sub-surface sediment than at the surface. The K/Al ratio in K-feldspars is appreciably higher than that found in muscovite (or illite).

Because of the large percentage of Mg in the seasalt admixed with the dried sediments, it is difficult to infer any geochemical trends in Mg. The Mg content as seen in the sediments

of core S 25 almost certainly reflects the abundance of contained seasalt, as does most of the variability of Mg in other sediment cores.

The element/Al ratios for both surface and sub-surface data in Table 4. 2 do not show any obvious areal variations.

b) The geochemistry of Fe, Ca and P

The ratios of Fe and Ca to Al in the 'normal' sediments (i.e. core S 25) are similar to those quoted for other sediments in Table 4. 2. Although Fe preponderates in detrital alumino-silicates here, the average Fe/Al ratio of 0.77 indicates the presence of some non-silicate Fe (e.g. Fe-oxides). Ca is most likely contained in plagioclase (and amphiboles) rather than calcite. The extremely low carbonate-C content in the sediments of core S 25 (Table 4. 1) confirms this opinion. In contrast, the input of Fe, Ca and P by man-made sources appears to represent a significant proportion of the southern sediments, and their distribution at the surface reflects the relative amount of accumulated effluent and natural sediment. This is demonstrated in Figs. 4. 4-6 which show the distributions of Fe, Ca and P respectively. The natural input of the same elements may be inferred from the analyses of Fe, Ca and P in the sediments of core S 25 (5.6% Fe, 21% Ca and 0.06% P). The contents of Fe, Ca and P in the sediments (Figs. 4. 4-6) in excess of the values quoted above are likely to be due to industrial contamination. It is evident from Figs. 4. 4 and 4. 6 that Fe and P are most abundant in the sediments close to the industrial source (D.N.Z., Fig. 1. 5). The distribution of Ca suggests that the accumulation in the sediments occurs some distance from the present source (see 6. 2 for discussion).

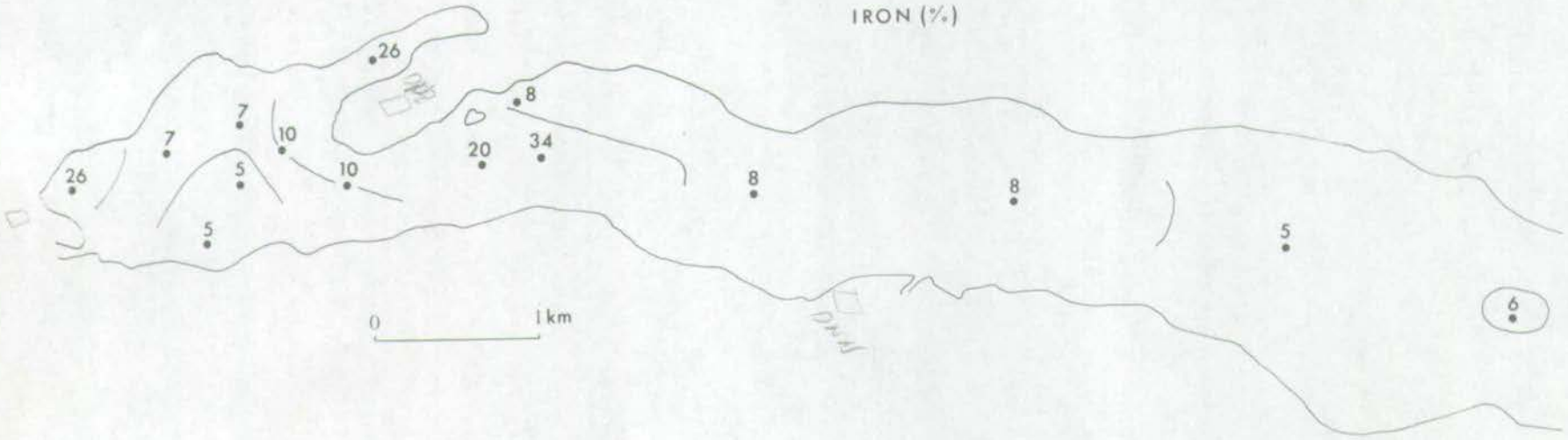


Fig. 4.4. Distribution of Fe in surface sediments of the southern part of Sörfjorden (contour lines at 6 and 10 wt.%).

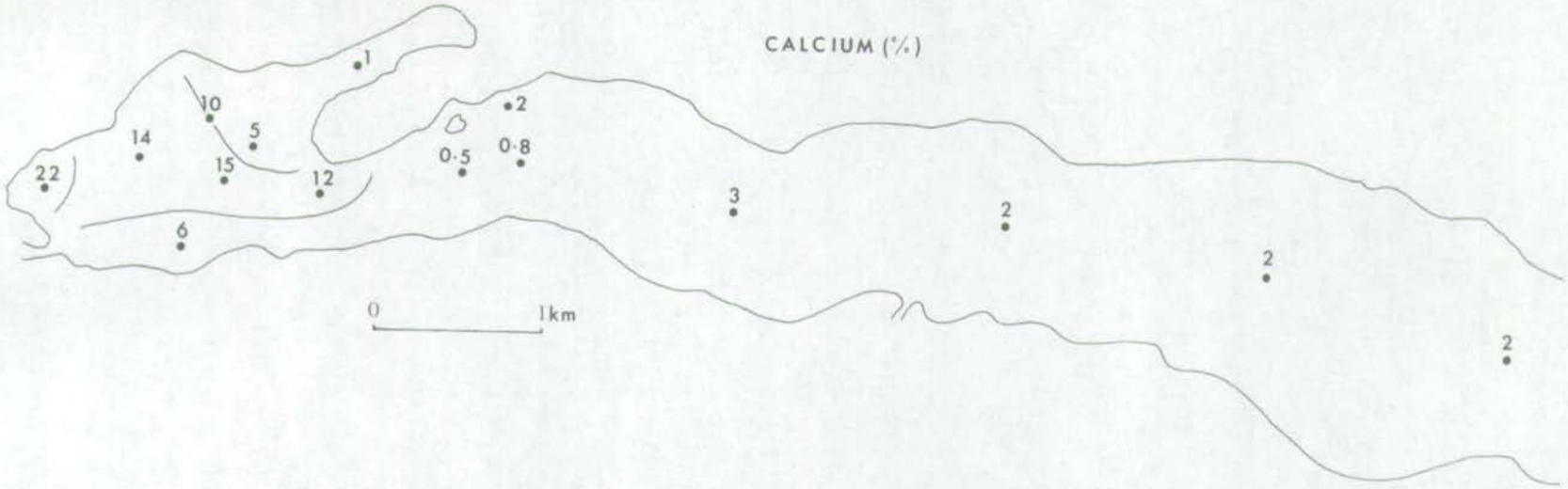


Fig. 4. 5. Distribution of Ca in surface sediments of the southern part of Sörfjorden (contour lines at 10 and 20 wt.%).

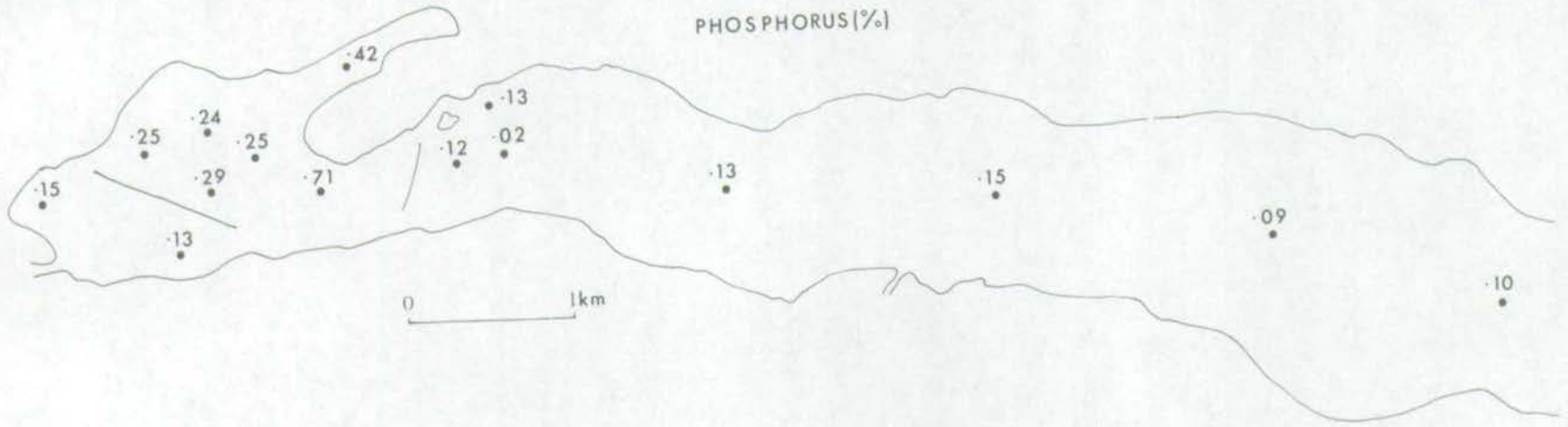


Fig. 4.6. Distribution of P in surface sediments of the southern part of Sörfjorden (contour line at 0.2 wt.%).

A concentration of Fe in excess of 6% occurs in sediments extending northward to the Digranes Sill (Fig. 4.2). Samples showing anomalous P values are more aerially confined, being restricted to the vicinity of the harbour basin. This may be due to an immediate sedimentation of discharged apatite (Table 2.4) and to a lesser extent accumulation of sewage sludge (p. 14). The dissemination of Ca from D.N.Z. (Fig. 1.5) appears to extend only ~3 km northwards.

c) The geochemistry of Mn

The importance of the geochemistry of Mn in marine sediments justifies a separate discussion of its distribution in Sörfjorden.

In addition to the analyses of Mn in cores collected during cruises A and B, all surface samples (0-2 cm) of cores collected during cruise I were also analysed for Mn (Table D 3, Appendix D).

The distribution of Mn concentrations in the surface sediments of the southern parts of Sörfjorden shows that Mn rarely exceeds 1000 ppm (Table D 2-3, Appendix D). Two local areas of high concentrations occur, that is close to the industrial effluent sites from D.N.Z. (Fig. 1.5), where concentrations of 1216 ppm and 2749 ppm Mn were measured and in the deep-water sediments (~ 400 m) of the north, containing maximum 2440 ppm Mn. In the former instance the Mn is almost certainly held with Fe. It is not known if this Mn is a direct effect of industrial discharge or is the result of scavenging of Mn by Fe-oxides. Certainly Mn/Al ratios in these sediments are far higher than those observed in detrital

alumino-silicates in the average shale (Krauskopf, 1967). The distribution of Mn/Al values in the south (Fig. 4.7) follows a pattern similar to Fe (Fig. 4.4), supporting the view that Mn and Fe are associated in these sediments. The higher Mn concentrations in the surface sediments from the north may also be associated with Fe but it is unlikely that this is the direct result of industrial discharge. It is well-known that many sediments displaying oxidizing surfaces tend to be enriched in Fe and Mn (Price, 1967; Burell and Hoskin, 1970; Doff, 1970, Taylor, 1974). The extent of Mn enrichment in the surface sediments within a particular basin having a constant input and a constant precipitation of MnO_2 appears to be related to total sediment accumulation rate; a slower rate results in higher Mn enrichment as the rate of dilution by other components (e.g. terrigenous alumino-silicates) is less. Hence, sediments accumulating in the deeper parts of the north, further removed from the main source of terrigenous alumino-silicates, are likely to be more enriched in Mn at their surface than other sediments.

The longitudinal profile of Mn (Fig. 4.8) shows some southern increase in concentrations between S 40 and S 43. However, south of S 43 there is a regular decrease of Mn towards Odda. The decrease in Mn is unlikely to be only due to dilution by industrial waste, as contents of Fe and Ca, the dominant pollutants, are not notably higher at stations immediately to the south of S 43 than those observed to the north (Table D 2, Appendix D). Certainly they do not show a change which communsurates with the twofold decrease

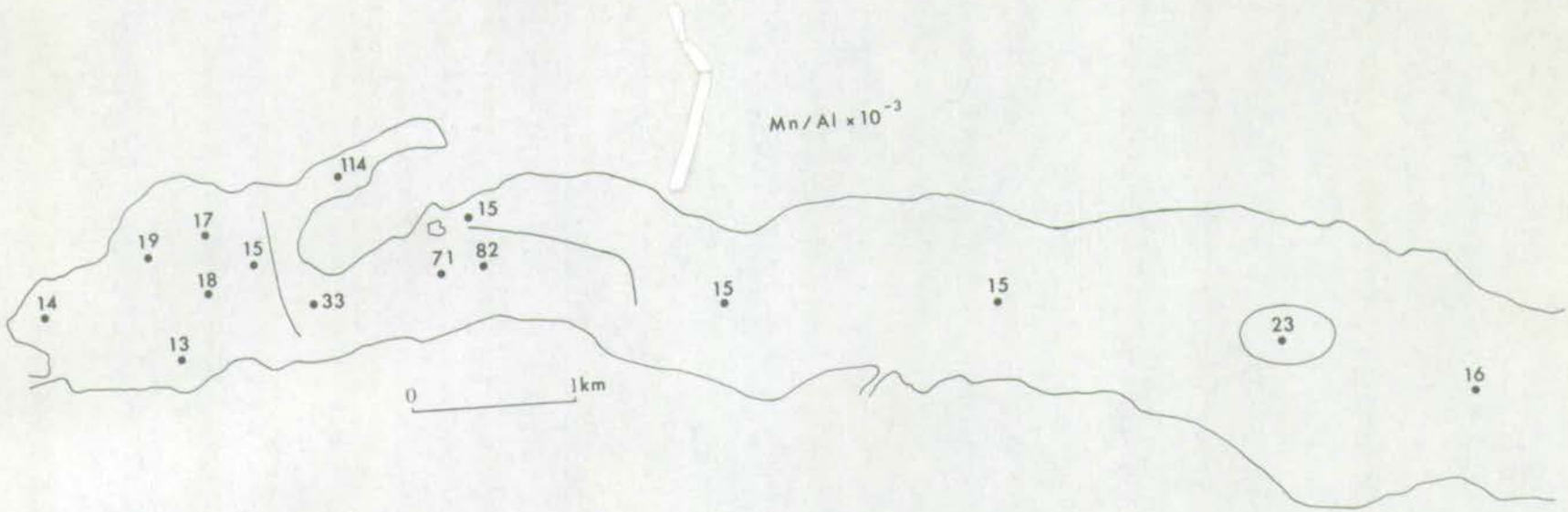


Fig. 4.7. Distribution of Mn/Al ratios in surface sediments of the southern parts of Sörfjorden (contour line at 20 x 10^{-3}).

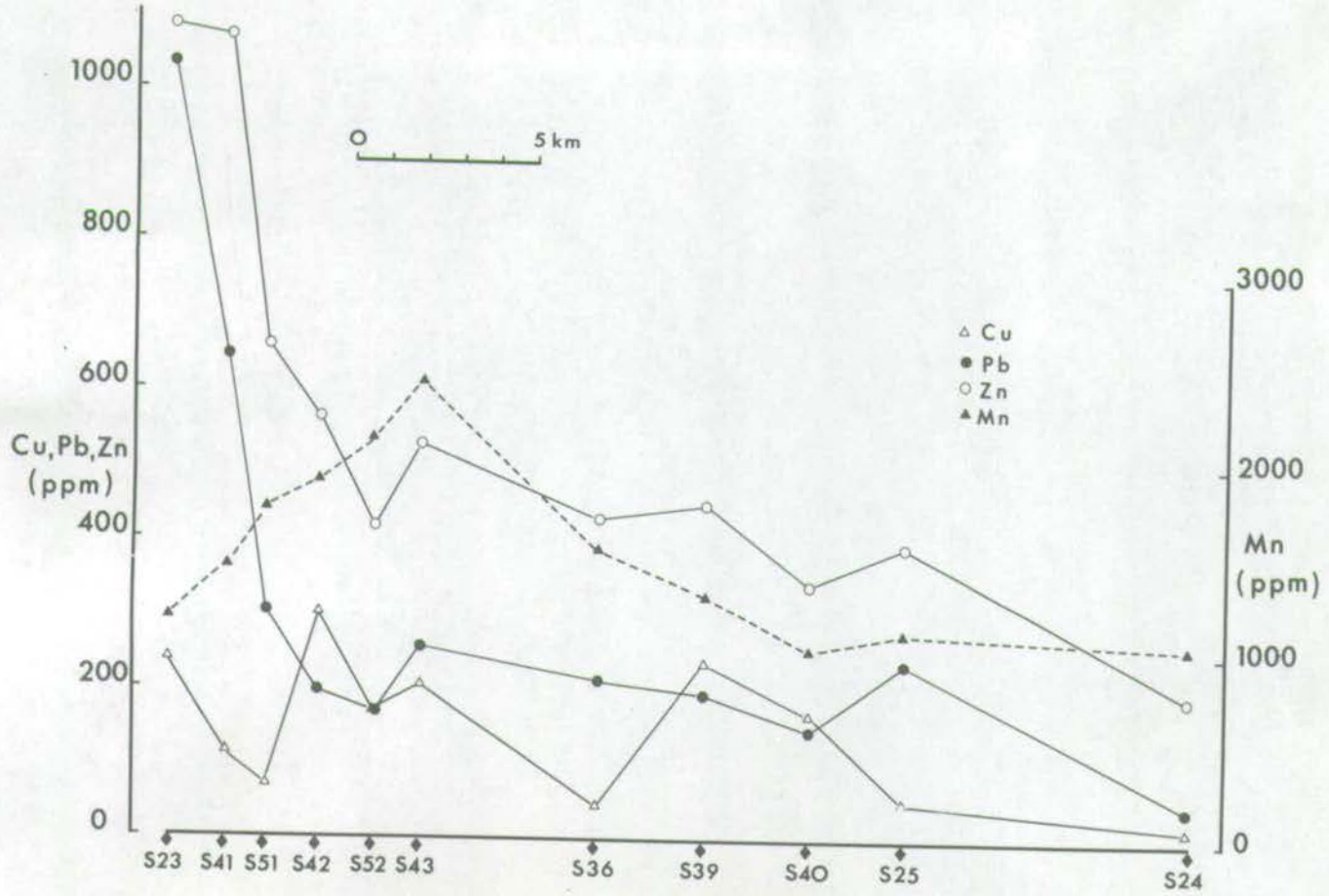


Fig. 4. 8. The longitudinal profiles of Mn, Cu, Pb and Zn in surface sediments for the central and northern parts of Sörfjorden.

in Mn concentrations south of this location. If the content of Mn in surface sediments is inversely related to total sediment accumulation rate, as suggested above, its change in concentration to the north and particularly to the south of S 43 could imply areal changes in the accumulation rates. The mechanisms of sedimentation and sources of sediments are discussed in Chapter 10.

d) Total-C

Total-C was only measured in the southern sediments and in cores S 24 and S 25. In the latter core both carbonate-C and organic-C were assessed. The 'anomalous' sediments display a wide range of total-C (Table 4.1 and Fig. 4.9). The unusually high total-C values in the surface sediments of the harbour basin coincide with an abundance of calcite (4.3) and Ca (Fig. 4.5). The accumulation of $CaCO_3$ is particularly high on the west side of the harbour basin (see 6.2 for discussion).

In core S 25 near the entrance to Sörfjorden carbonate-C concentrations are very low (< 0.01-0.06% CO_2) (Table D2, Appendix D) suggesting that virtually no biogenic carbonate material exists in the sediment. Organic-C in the same sediments also appears low (0.55-1.21% C). It is noteworthy that S 25 displays some surface enrichment of organic-C; C values range from $\sim 0.5\%$ at 15 to 20 cm to values exceeding 1% near the surface of the core. This pattern is consistent with many geochemical observations in oxic fjords (Taylor, 1974) and coastal sediments in general, and may be related to bacterial attack (Hallberg, 1973) and combustion of organic matter at or near the surface of sedimentation. Alternatively it may imply

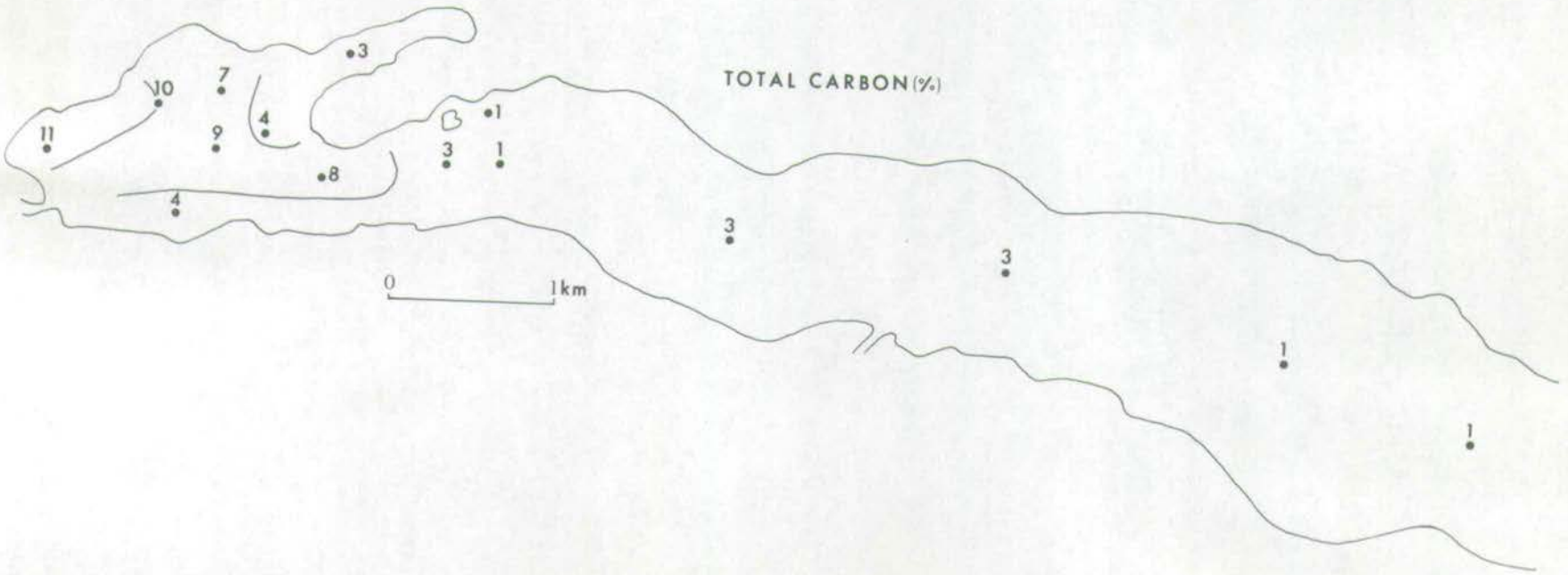


Fig. 4. 9. Distribution of total-C in surface sediments of the southern parts of Sörfjorden (contour lines at 5 and 10 wt.%).

either a change in organic matter production and fallout onto the bottom sediments, or a varying rate of accumulation of the inorganic components of the sediment.

4.4. Geochemistry of the trace elements

The distribution of trace elements (Ag, Ba, Bi, Cd, Cu, In, Pb, Sb, Sn, and Zn) in the 'anomalous' sediments of Sörfjorden is described in Skei et al.(1972) (Appendix E). Only three elements (Cu, Pb and Zn) have been analysed for all the cores, and the discussion on minor elements will be entirely confined to these.

As with the major elements, the areal distribution of minor elements in the surface sediments can be divided into 'normal' and 'anomalous' sediments in the northern and southern parts of the fjord respectively. Additionally because of the wide range in concentrations of minor elements (Table 4.3), one can conveniently include an 'intermediate' zone. The arbitrary limits of the 'anomalous' sediments include those sediments occurring south of the Digranes Sill (Fig. 4.2). 'Normal' sediments include only cores S 24 and H 47-49 (see Fig. 4.1). In order to assess the background level of Cu, Pb and Zn, the uppermost 60 cm of sediments from core S 39 were analysed, and the mean metal contents below 15 cm depth are used as a base line (Fig. 4.10). Surface concentrations of Cu, Pb and Zn that exceed these mean values are assumed to be the result of surface metal enrichment, by either contamination from industrial discharge or by natural processes, as discussed on p. 114 . From the tabulated results in Appendix D it is evident that some cores show levels of Cu, Pb and Zn in the sub-surface sediment, for instance

Table 4. 3. Cu, Pb and Zn in surface sediments from Sörfjorden and other fjords

	1	2	3	4	5
Cu	2287	137	61	62	25
	96-12000	45-304	7-138	54-69	18-28
Pb	10745	260	80	53	51
	720-70000	141-642	17-140	50-56	44-62
Zn	18895	531	203	145	136
	830-118000	340-1068	172-269	133-160	129-145

1. Average and range of 17 'anomalous' surface sediments (Sörfjorden)

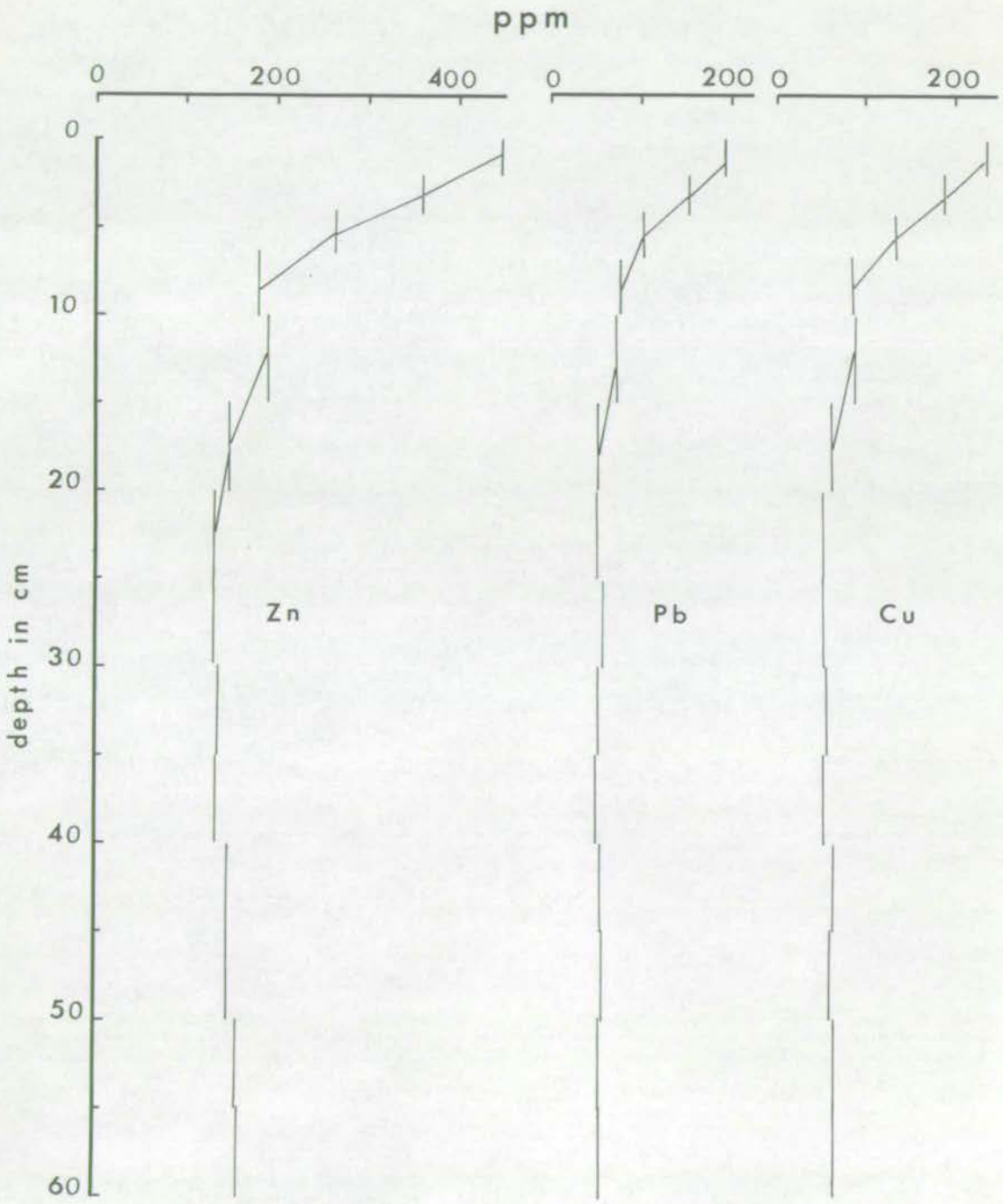
2. Average and range of 9 'intermediate' surface sediments (Sörfjorden)

3. Average and range of 4 'normal' surface sediments (Sörfjorden)

4. Average and range of 9 sub-surface samples from core S 25 (base line)

5. Average and range of 5 oxic surface fjord sediments (Taylor, 1974)

Fig. 4.10. Vertical distribution of Cu, Pb and Zn in core S 39.



10-15 cm depth, which are lower than the quoted base line values. Such low metal values are coincident with isolated sand horizons in the sediment (p. 42).

Table 4.3 lists the mean and range of Cu, Pb and Zn concentrations in surface sediments of 'normal', 'intermediate' and 'anomalous' types in Sörfjorden, as well as base line and actual concentrations of these elements in fjord sediments from other areas. Within the 'anomalous' area Cu, Pb and Zn are strongly interrelated (Skei et al., 1972, Appendix E). However, these correlations become less obvious northwards. Both Zn/Cu and Pb/Cu ratios decline in sediments progressively northward from Odda (Table 4.4). In contrast, Zn/Pb ratios show a marked decrease from north to south. In the extreme south, the Zn/Pb ratio is similar to that found in the effluent, i.e. Zn/Pb = 1.3. This is not true for Zn/Cu and Pb/Cu ratios in the sediments, which show much lower ratios than that found in the effluent (i.e. Zn/Cu = 20; Pb/Cu = 15). These differences are to some extent due to varying amounts of soluble and insoluble metals in the effluent. Additionally, there may be differences in the behaviour of metals in the fjord with respect to mechanisms of organic uptake, including chelation etc. (see Hallberg, 1973). Also a varying proportion of the metals in the surface sediments, especially in the north, may be a result of a normal sediment loading at the surface of sedimentation, which is likely to display different metal ratios.

A profile of surface concentrations of Cu, Pb, Zn (and Mn) for sediments located along the median line of Sörfjorden from

Table 4.4. Interelement relationships of Cu, Pb and Zn in surface sediments

	1	2	3	4	5
Zn/Cu	7.2	5.8	4.6*	2.4	5.5
Zn/Pb	1.8	2.2	2.8	2.7	2.7
Pb/Cu	4.7	3.0	1.4+	0.9	2.1

1. Average and range of 17 'anomalous' surface sediments (Sörfjorden)
2. Average and range of 9 'intermediate' surface sediments (Sörfjorden)
3. Average and range of 3 'normal' surface sediments (Sörfjorden)
4. Average and range of 9 sub-surface samples from core S 25 (base line)
5. Average and range of 5 oxic surface fjord sediments (Taylor, 1974)

* one extreme value of Zn/Cu = 24.57 is omitted (H 47, 0-2 cm)

\+ one extreme value of Pb/Cu = 9.14 is omitted (H 47, 0-2 cm)

station S 23 northwards is presented in Fig. 4.8. Even though there are areal variations in Zn/Pb ratios, as mentioned above, longitudinal profiles of Pb and Zn are very similar and show general increases southwards towards Odda, (see also Fig. 7 in Skei et al., 1972, Appendix E). Only in the most southern section of this profile (south of S 52) is there a rapid rise in metal concentration. The profile of Cu in many respects is very different from Pb and Zn; the Cu content varies considerably between adjacent stations, and does not show an obvious increasing tendency southwards. Unusually high Cu concentrations occur only in sediments south of S 23 (Fig. 7 in Skei et al., 1972, Appendix E). Clearly the processes of Cu sedimentation are different from those of Pb and Zn. Moreover, Cu concentrations of the northern sediments (S 24, 25) are not notably higher than base line values, implying that unlike the southern area, the enrichment of Cu in the surface sediments here is small or non-existent.

The average content of Cu in the 'anomalous' sediments (Table 4.3) is ~16 times higher than the corresponding value for the 'intermediate' sediments. The maximum concentration measured in the surface sediments (12000 ppm) is far above maximum levels reported in polluted sediments of New York Bight (Cu_{max} = 390 ppm; Carmody et al., 1973) and the Clyde Sea (Cu_{max} = 172 ppm; Steele et al., 1973). Similarly, highest concentrations of Pb and Zn (7% and 11.8% respectively) exceed those of most studies on pollution. Sediments collected in the vicinity of a zinc melt in the Severn Estuary, England, contained 200 ppm Pb and 590 ppm Zn

(Butterworth et al., 1972), demonstrating clearly the severity of the metal contamination in sediments from Sörfjorden by comparison.

PART IV

WATER CHEMISTRY

INTRODUCTION TO CHAPTERS 5 TO 9

The following chapters will be concerned with the composition and distribution of suspended particulate matter, as well as certain dissolved constituents, in Sörfjorden.

Most studies of suspended particulate matter ($> 0.45\mu$) in marine waters are confined to gravimetric analyses (Banse, 1963; Jacobs and Ewing, 1969a; Bassin et al., 1972) and/or in situ optical measurements (Jerlov, 1955; Jacobs et al., 1973). A few studies have been conducted on the size distribution of particles (e.g. Burell and Hadley, 1971; Sheldon et al., 1972) and the mineralogy of suspended matter (Jacobs and Ewing, 1965; Beer and Gorsline, 1971). Recently more attention has been directed towards its elemental composition (Spencer and Sachs, 1970; Price and Calvert, 1973; Price and Skei, 1975). On the basis of these works it was thought that a major study of the composition of suspended particulate matter would assist in understanding some of the problems of circulation and its bearing on the transport of natural elements and pollutants within Sörfjorden.

Suspended particulate matter in natural waters is essentially composed of four main components: terrigenously derived inorganic matter, biogenous skeletal constituents, organic matter and authigenic phases. The identification and characterisation of these constituents, expecially the first two, on the basis of chemical composition is difficult because of partitioning of elements between different components. Such identifications have rarely been successful. This is largely due to the partial or incomplete assessment of composition of

the particulate matter. For this reason, most chemical investigations of particulate matter have to date been confined to the geochemistry of one or two elements (Joyner, 1964; Atkinson and Stefansson, 1969; Betzer and Pilson, 1970).

The problems of studying the particulate matter in Sörfjorden in many respects are made more complicated than those outlined above, because of the emergence of a variety of chemical pollutants from the industry about Odda. Hence, in addition to the four main components in particulate matter quoted above, certain pollution phases must be included.

In this study of the composition of the major and minor constituents of particulate matter collected within Sörfjorden at stations shown in Fig. 3.1 and Tables A 1-2, Appendix A, the following elements Ca, K, Fe, Ti, Si, Al, Mg, P, Mn, S, Cu, Pb and Zn have been investigated. These elements were analysed by X-ray fluorescence analysis following the method of Price and Calvert (1973), Skei et al. (1973) and Taylor, 1974 (Appendix C). Those stations where particulate matter was collected in 1971 are shown in Skei et al. (1973) and those occupied in Hardangerfjorden, in Price and Skei, 1975 (Appendix E). Gravimetric measurements of the total suspended matter, mineralogical (XRD) and scanning electron microscope (S.E.M.) examinations were conducted on selected samples (Appendix C). More detailed description of the sampling and analytical methods are included in Appendices A, B and C and a complete set of tabulated data is presented in Appendix D.

Filtered water samples were analysed for dissolved Fe,

Mn, Cu, Pb and Zn using methods shown in Appendix C. Data on dissolved constituents are generally incomplete (Appendix D).

Within fjords it has been shown (Chapter 3) that the circulation of both surface and deep waters are liable to periodical or seasonal changes. Such changes are likely to affect both the amounts and composition of certain particulate constituents (Chapters 5 and 6). For this reason the collection of water and the filtering of its particulate matter were undertaken at different times, expressly at different seasons but unfortunately not in the same year, so that some assessment of compositional variations in the particulate matter could be made. In this respect, it is hoped to improve our information on the partition of elements between the different phases, in relation to productivity (Chapter 6) and runoff, (Chapter 5). Data on hydrography and hydrochemistry have also shown some secular change in the bottom waters. Hence, attention has been paid to the chemistry of the particulate matter in these waters (Chapters 7 and 9), as it may assist the understanding of several problems associated with bottom sediment resuspension and nepheloid layers in general.

In addition to the study of major components, investigations have also been made on particulate minor elements, i.e. Cu, Pb and Zn (Chapter 8) and also on dissolved metals (Chapters 7 and 8). The aims of these investigations are broadly consistent with those mentioned above, and will be used, in particular, to understand the dispersal of industrial pollutants.

CHAPTER 5

THE DISTRIBUTION AND COMPOSITION OF THE TERRIGENOUS CONSTITUENTS OF SUSPENDED PARTICULATE MATTER.

Before examining the major element chemistry of terrigenous derived suspended matter, it may be advantageous to consider the distribution of total suspended matter (TSM) in the water and its mineralogy.

5.1. Total suspended matter (TSM)

The total amount of suspended particulate matter (TSM) retained by a preweighed 0.4 μ membrane filter was obtained for isolated water profiles at various times (Table D 4, Appendix D). Concentrations during high runoff (August 1971/72) vary between 400 and 3300 μg/kg water, consisent with the range observed in other fjord waters (Folger et al., 1972). The highest concentrations are found above the pycnocline, where they appear to be areally consistent. However, as shown in 5.4 there appears to be a seaward decrease in detrital alumino-silicates in the surface water. Hence the uniform concentration of TSM in these surface waters indicates that there must be a complimentary increase of particulate organic matter. A seaward increase in particulate organic matter has also been observed in the St. Lawrence estuary, Canada, where TSM consisted of 10 to 40% organic matter in the upper part of the estuary, compared with >50% in the lower estuary (D'Anglejan and Smith, 1973).

Samples collected in September 1973 (Cruise II) when the volume of runoff was smaller, contained 45 to 500 μg/kg TSM in Sörfjorden and 15 to 360 μg/kg in Hardangerfjorden. As these concentrations are generally below the minimum value measured at high runoff, it appears that the most intense period of suspended sediment transport in the fjord occurs during high river discharge (cf. Allen and Castaing, 1973; Bornhold et al., 1973). The concentrations of TSM collected at minimum runoff (April 1974, Cruise III) were only measured for the Hardangerfjord samples. These show a wide range in values, from 15 to 890 μg/kg. The highest concentrations were seen in the upper waters, particularly at 25 m depth, largely due to the abundance of planktonic matter (Price and Skei, 1975, Appendix E)

The concentrations of TSM in the deeper waters of Sörfjorden are approximately one order of magnitude higher during high than at medium runoff. This is almost certainly due to settling out of particulate matter from a sediment-laden surface plume. Occasional high TSM values measured in the bottom water at various times (e.g. September 1973, S59), may be due to a resuspension of bottom sediments (Chapter 9).

Without measurements of particulate organic matter it is difficult to obtain real estimates for the proportions of organic and inorganic constituents in different waters. However, some estimate of the concentrations of the former constituent can be obtained by subtracting the mass of major inorganic elements calculated as their respective oxides, from values of TSM. Using these results

the proportion of organic to inorganic matter varies appreciably in the fjord waters. For instance, during September 1973, ~50% of the particulate matter occurred as organic matter within the uppermost 50 m of various water profiles. In the deeper waters the proportion of particulate organic matter decreased to ~25%. During a period of high productivity (April 1974), 80 to 95% of the particulate matter in the euphotic layer of Hardangerfjorden, occurred as organic matter. These percentage values are consistent with data obtained elsewhere. For instance, Manheim et al. (1970) estimated that 60 to 90% of the TSM in surface waters over continental shelves was organic matter.

5. 2. The mineralogy of suspended particulate matter

X-ray diffraction analyses were performed on particulate matter held on 'Sartorius' and 'Nuclepore' membrane filters, 'Whatman' glassfibre filters and 'Selas' silver filters, so that a comprehensive assessment could be made on all the possible minerals present. However, due to the insensitivity of these analytical techniques it was possible to identify only a few minerals and these could not be quantitatively assessed.

Both illite (10Å) and chlorite (7Å, 14Å) are present in most surface samples. Illite (10Å) generally showed a very much more intense reflection than chlorite (7Å) (cf. Spencer and Sachs, 1970), in both the suspended matter of the river Opo entering Sörfjorden and in the particulate matter of the fjord. Such observations are in agreement with Tucholke (1974) who has claimed that suspended particulate matter is illite-enriched.

Of other naturally occurring minerals, both feldspar (3.16Å and 3.22Å) and amphibole (8.5Å), were observed in a few samples, the latter being found only in water of the river Ullensvang. Quartz was not positively identified in any of the samples analysed. Such a lack of identification is not due to the masking of its principal reflections by cellulose, as it was unobserved in samples mounted on 'Nuclepore' and 'Selas' silver filters.

Both calcite (3.03Å) and gypsum (7.57Å) were present in some sub-surface samples collected in the immediate vicinity of the H_3PO_4 plant near Odda (S 26, S 31 and S 64).

5. 3. Major element chemistry of the terrigenous derived particulate matter

The chemistry of the particulate matter is complicated by having several of its constituent elements partitioned between two or more of the main components (p. 55). Nevertheless, an attempt will be made, where possible, to consider first of all the geochemistry of elements residing in terrigenous derived alumino-silicates. Particulate Al is held almost exclusively in alumino-silicates (Joyner, 1964; Spencer and Sachs, 1970). For this reason Al has normally been used as a measure of the total inorganic silicates. While Mg, K and Ti also preponderate within silicates (Hirst, 1962), a portion of Mg and K may be adsorbed on clay minerals as well as on authigenic constituents (Posselt and Anderson, 1968; Taylor, 1974). Ti may be associated with colloidal Fe as well as detrital alumino-silicates (Isayeva, 1971). Further, there is some evidence that all these elements also concentrate in plankton. Riley and Roth

(1971) and Martin and Knauer (1973) report high concentrations of Al and Ti in phytoplankton and Nicholls et al. (1959) and Szabo (1968) measured considerable quantities of Ti in plankton. Unfortunately a close inspection of much of the data in these quoted works (e.g. Martin and Knauer, 1973), revealed that a proportion of these elements could be held in contaminating alumino-silicates. Even so, both K and Mg are known to be abundant in plankton, with possibly higher concentrations of K and Mg residing in phytoplankton than zooplankton (Fujita, 1971). It appears that K predominates over Mg in these organisms, the mean K/Mg ratios being 11.6 and 2.0 respectively (Fujita, op. cit.). The assumption that Al is dominantly associated with alumino-silicates is further complicated by the likelihood that Al from industrial waste contaminates certain waters (Table 2.4). The results of this are seen in the unusually low Si/Al, Ti/Al, K/Al and Mg/Al ratios in both surface and some sub-surface waters in the vicinity of Odda (Table D 7, Appendix D). However, Ti strongly correlates with Al in uncontaminated fjord waters (Price and Calvert, 1973) and Ti can be employed as a substitute of Al when assessing the quantities of alumino-silicates in the fjord.

5. 4. Distribution and transport of detrital alumino-silicates

Typical profiles of particulate Al for water stations in Sörfjorden are presented in Fig. 5. 1. The most striking feature is the almost horizontal zone of maximum concentration occurring above the halocline (= pycnocline, p. 20)(cf. Meade, 1972). There is obviously a close relationship between the density of the water and the distribution of Al (Fig. 5. 2). Only at times of low runoff

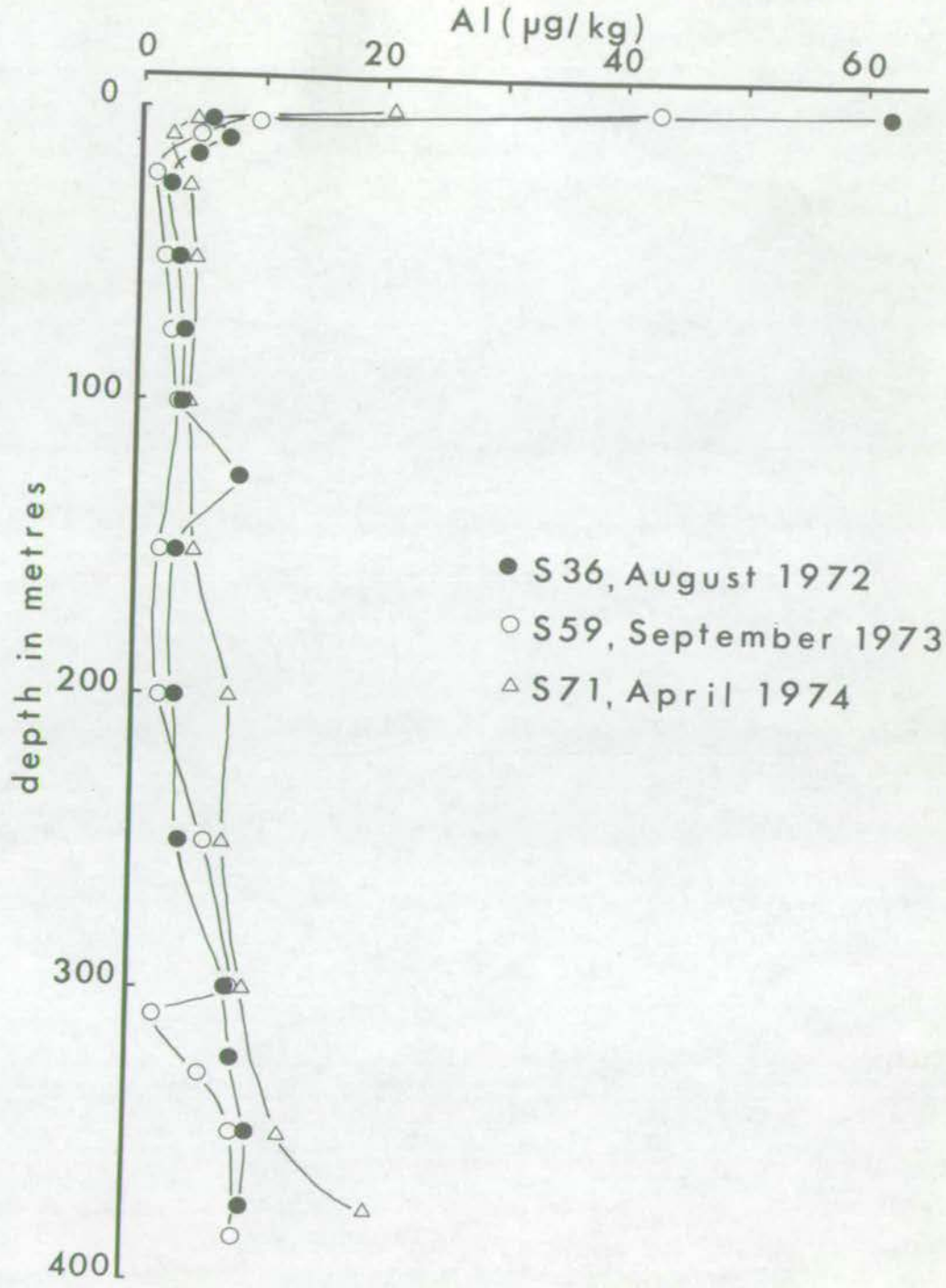


Fig. 5.1. Variations in the vertical distribution of particulate Al at periods of different runoff.

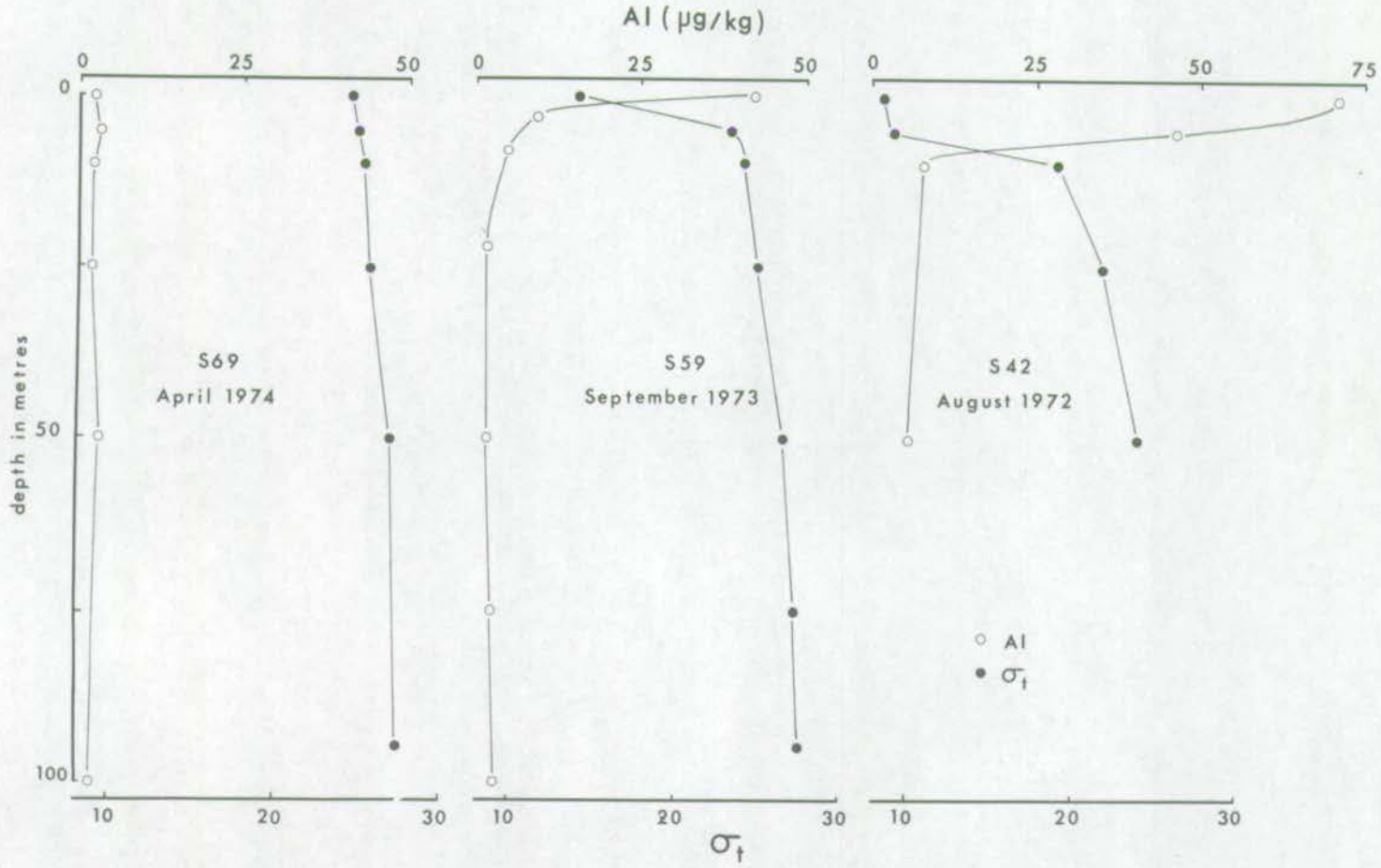


Fig. 5.2. The relationship between particulate Al and the density of the water (σ_t) at various states of runoff.

(e.g. April 1974), when the upper waters are essentially isohaline, are there no obvious maxima at the surface (Fig. 5.2). These results tend to conform with the view that the pycnocline acts as a physical barrier to the settling of alumino-silicates (Postma, 1967; Taylor, 1974). Further, it is believed that due to the increasing current velocity towards the seawater-air interface (e.g. Pickard and Rodgers, 1959), maxima of detritus are observed at the surface and not at the halocline.

With some knowledge of the hydrography of the fjord's waters, it would appear that the governing factors controlling both the dispersal and deposition of detrital silicates are the density stratification, coupled with this the movement of water masses. An upper water estuarine circulation of surface outflow and a consequent inflow below has been established in Sörfjorden for all seasons (Chapter 3). It has also been suggested that the extent of this circulation is almost certainly dependent on the level of freshwater runoff. Variations in runoff obviously control the amount of detritus entering the fjord.

During the period of highest runoff (August 1972, Cruise I) when the surface waters (10-18 m) have a net outflow, the concentration of particulate Al decreases from ~500 µg/kg in the river Opo, the dominant source of particulate matter for the fjord, to ~62 µg/kg in the surface waters near the mouth of the fjord (S 34). If the observed decrease in particulate silicates in the surface flow is a direct consequence of the mixing between suspended loaded river water and high-salinity inflowing water (carrying small quantities of

detritus) one would expect an inverse relationship between salinity and detrital silicates (cf. Meade, 1968). The trend of this relationship is indicated in Fig. 5.3, using particulate Ti to denote the alumino-silicates. Although the salinity (S) ranges are somewhat limited, the plots of Ti against S all fall well below the dilution line. It is obvious that the concentration of Ti, and hence alumino-silicates, is non-conservative within the fjord. The shape of the curve implies much removal through fallout of alumino-silicates in the surface waters. This trend contradicts the assumption of Sachett and Arrhenius (1962) who proposed that particulate Al could be used as a tracer to establish mixing of river water and seawater (see also Joyner, 1964).

A small increase of detrital silicates sometimes occurs at or close to the breaking point between the halocline and the lower zone (i.e. surface of no-net-motion, p. 31). This is best seen at stations S 36 (10 m) and S 41 (15 m) (Table D 5, Appendix D). A similar accumulation of sediment along the intersection of the level of no-net-motion has been observed in the James River Estuary (Nicholls, 1972), in waters off California (Beer and Gorsline, 1971) and in fjord waters (Taylor, 1974).

Within the compensating current, the concentration of alumino-silicates is much lower than at the surface, but its concentration trend is superficially very similar in that it increases towards the head of the fjord. It would appear that the inward increase in alumino-silicates in the sub-surface water must be caused by some entrapping mechanism (cf. Postma, 1967).

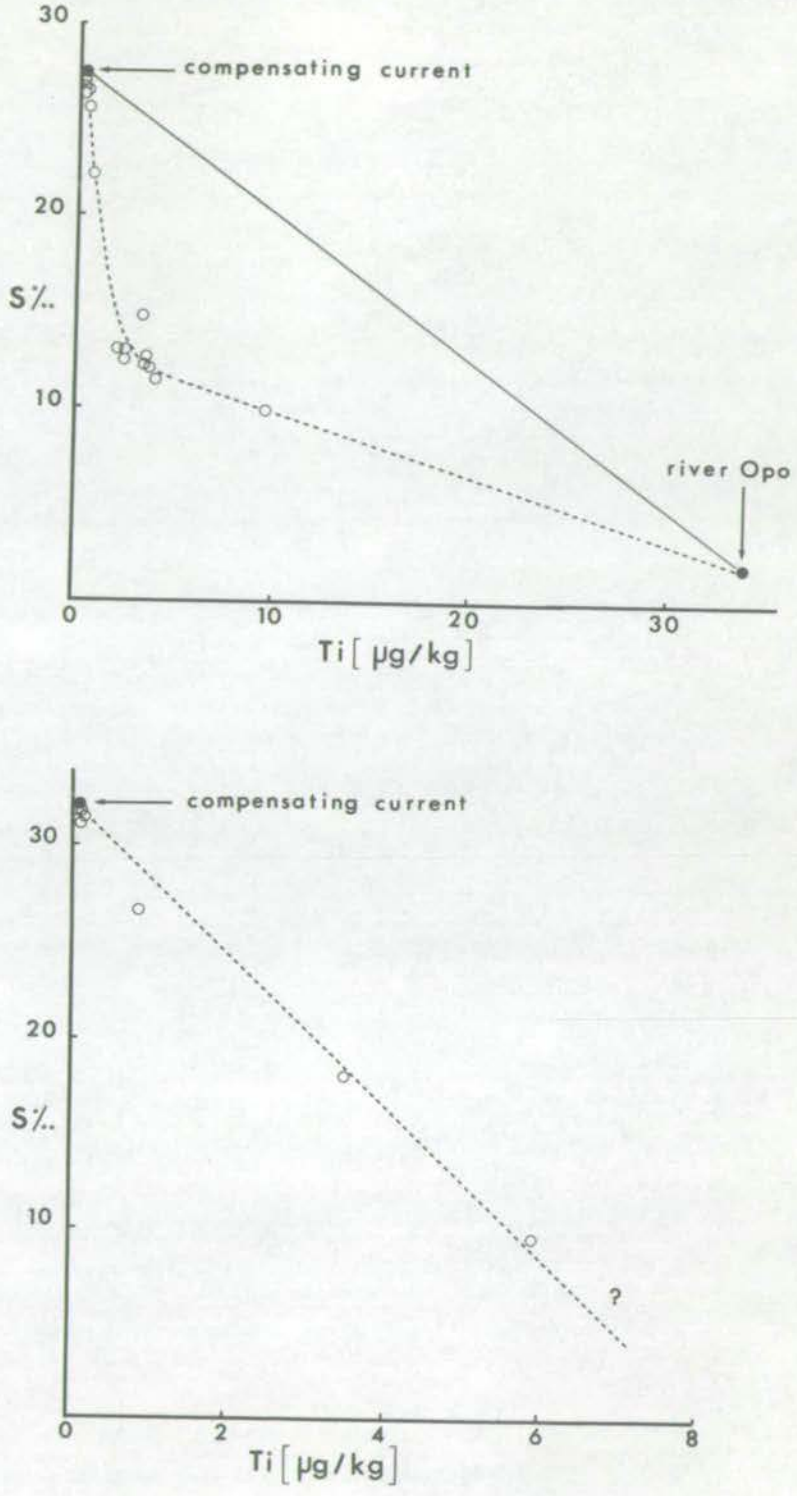


Fig. 5. 3. The relationship between particulate Ti and salinity (S) in the surface water at high runoff (August 1972) and low runoff (April 1974).

Waters below the compensating current during this period of high runoff show relatively constant Al concentrations (see Fig. 5.1). Only in the bottom water (> 250 m) is there some increase in Al and other elements indicating alumino-silicates (i,e. Mg, K and Ti). Bottom water concentrations of alumino-silicates are approximately three times those of the intermediate waters, but represent only one sixth of that observed in the surface water. This increase in the bottom waters is likely to be due to a moderate resuspension of bottom sediments (see Chapter 9).

During periods of moderate runoff (e.g. September 1973, Cruise II), the concentration of Al in the surface water is only some 60% of that observed during high runoff (Cruise I). The sub-surface waters are also lower in Al. For instance, between 25 and 200 m concentrations of Al range between 0.6 and 2.8 μg/kg (S 59), compared with 2.3 and 8.1 μg/kg during high runoff (Fig. 5.1). However, in the bottom waters Al increases fourfold over the intermediate water values and again implies bottom sediment disturbance (Chapter 9).

In the southernmost part of the fjord (S 64 and S 63), the distribution of particulate Al, Ti, Mg and K is somewhat unusual. Here, and only during this period (September 1973), waters between 30 and 90 m (S 63) show an abundance of alumino-silicates and pollutants (particulate Ca, P, Fe, Zn and Pb). The same feature is also apparent at S 59 (75-100 m) and S 58 (90-100 m) (Table D 5, Appendix D). This anomaly is thought to be related to the near surface inflow of coastal water described in 3.7. During its reversal

to form or contribute to the outflow of water from the harbour basin near Odda, it is thought to cause considerable resuspension of bottom sediment. This phenomenon is further indicated by comparison of the concentrations of Al in the bottom water of the harbour basin during August 1971 (Cruise B), when this form of inflow was absent, with those observed during September 1973 (Cruise II). For instance, concentrations of Al near the seabed at S 26 (the same position as S 64) sampled in 1971, are only about one third of that seen in 1973.

Aluminium concentrations measured for surface samples collected during the period of lowest runoff (April 1974, Cruise III) are only 30% of those measured at high runoff. The mixing relationship between alumino-silicates, described as before by Ti concentrations (p. 62) and salinity in the surface waters at lowest runoff, is demonstrated in Fig. 5.3. Unfortunately, the concentration of alumino-silicates in river Opo is unknown at this time. The trend of the data points approximates to an inverse linear relationship between salinity and particulate Ti in contrast to that observed at high runoff. This implies that during low runoff there is little fallout from the surface waters. This trend might be expected, as little coarse-grained detritus would be carried into the fjord under these conditions.

At intermediate depths during minimum runoff (April 1974), concentration of detrital silicates is somewhat greater than at other times (Fig. 5.1). Such a trend does not imply a greater fallout from the surface layer due to weak density stratification (cf. Fig. 5.3).

It is more likely that the higher Al concentrations are a result of bottom sediment resuspension that pervades both deep and intermediate waters (Chapter 9). An alternative or complementary explanation may be that this feature is associated with slow settling of smaller sized particles at this time. There is little evidence for water exchange in the deeper parts of the fjord (p. 38) during this period, and this as a consequence implies a longer residence time of the water and its suspended matter.

5. 5. The interelement relationship between Al, K, Mg and Ti

It has been recognized that much if not all the K, Mg and Ti in suspended particulate matter is associated with aluminosilicates (Price and Calvert, 1973). Hence, it would be desirable to establish the interelement relationships between these elements in order to evaluate or specify the composition of detrital aluminosilicates in different bodies of water and at different states of runoff. The means and ranges of K/Al, Mg/Al, Ti/Al and K/Mg ratios for the different periods of sampling are listed in Table 5. 1.

The strong correlation between K and Al in particulate matter is shown in Fig. 5. 4 from plots of data for stations S 36-40 (August 1972). This figure also shows that the K/Al ratios in particulate matter of the fjord waters are intermediate with respect to those of bottom sediments and river particulate matter entering Sörfjorden. The composition of the latter is quite variable. However, the river Opo, which dominates the runoff into the fjord, shows very high K/Al and K/Mg ratios of ~0.5 and ~2.1 respectively. As a consequence, when suspended matter is abundant in the fjord

Table 5.1 Means and ranges of element/Al ratios in particulate matter

	1	2	3	4	5	6	7	8
K/Al	0.50	0.41 (0.46)	0.33 (0.48)	0.30 (0.33)	0.38	0.37	0.30	0.29
	0.24-1.12	0.17-0.94	0.08-0.87	0.13-0.45	0.27-0.53	-	0.24-0.42	-
Mg/Al	0.32	0.33 (0.39)	0.43 (0.50)	0.24 (0.34)	0.29	0.23	0.26	0.17
	0.16-0.78	0.13-1.50	0.19-1.07	0.06-0.61	0.16-0.41	-	0.19-0.41	-
Ti/Al	0.045	0.054(0.054)	0.046(0.046)	0.049(0.045)	0.068	0.076	0.042	0.056
	0.031-0.073	0.040-0.084	0.025-0.080	0.020-0.113	0.041-0.081	-	0.033-0.072	-
K/Mg	1.58	1.28 (1.33)	0.79 (1.00)	1.44 (1.34)	1.48	1.57	1.23	2.20
	0.56-2.57	0.54-1.97	0.36-1.51	0.36-2.73	0.72-2.14	-	0.76-1.85	-

1. Average and range of 40 samples (Sartorius, 0.45μ). Cruise A, August 1971. Sörfjorden.
2. Average and range of 107 samples (Nuclepore, 0.4μ). Cruise I, August 1972. Sörfjorden and Hardangerfjorden (in brackets).
3. Average and range of 83 samples (Nuclepore, 0.4μ). Cruise II, September/October 1973. Sörfjorden and Hardangerfjorden (in brackets).
4. Average and range of 84 samples (Nuclepore, 0.4μ). Cruise III, April 1974. Sörfjorden and Hardangerfjorden (in brackets).
5. Average and range of 7 river/lake samples (Nuclepore, 0.4μ). Cruise I, August 1972. Sörfjorden
6. Average of 45 sediment samples from Sörfjorden.
7. Average and range of 58 samples from Loch Etive, Scotland (Sartorius, 0.45μ). (Price and Calvert, 1973)
8. Average shale (Krauskopf, 1967).

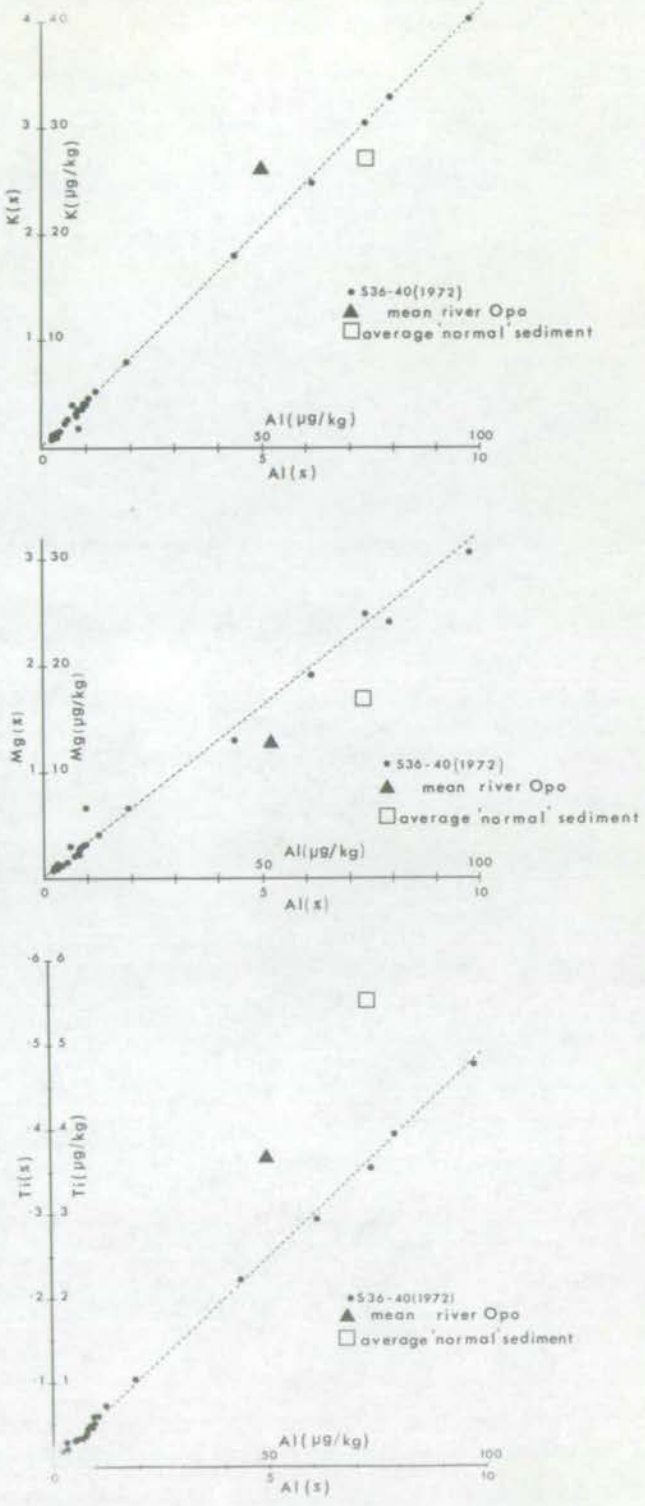


Fig. 5.4. Element-Al relationships in particulate matter from Sörfjorden, the river Opo (element concentrations x 10^{-1}) and in the sediment (element concentrations in wt.%).

water during periods of high runoff (August 1971 and 1972), the K/Al ratios are considerably higher than at other times (Table 5.1) (cf. Price and Calvert, 1973).

The discrepancy between the K/Al ratios of particulate matter and sediments may be due to mineralogical differences, but could also imply some contribution of organic-bound K (p. 62) in the particulate matter, which contains 40 to 90% organic matter (p. 60) in contrast to the sediment where organic matter comprises a much smaller proportion of the total. Suspended particulate matter is illite-enriched (p. 60) relative to the bottom sediment; the latter contains large quantities of quartz and other non-K bearing minerals (plagioclase and amphibole). Illite is known to be a high K clay (Russell, 1970), showing preferential adsorption of K from seawater (Harder, 1974). Higher K/Al ratios in particulate matter of fjord waters relative to the bottom sediments were also observed by Taylor (1974).

In the April 1974 data there is a noticeable southward decrease in K/Al ratios in the uppermost 100 m of water within Sörfjorden (Table D 7, Appendix D) (see also Fig. 5.5). Likewise, in September 1973 the particulate matter from the most southern part of the fjord displays low K/Al ratios, particularly at the surface and below 25 m depth. Such a trend is also seen in Mg/Al and Ti/Al ratios, suggesting that the low element/Al ratios relate to discharge of Al from industrial waste (p. 13).

As Mg normally resides within chlorites and some illite in detrital matter, its distribution should relate to the elements

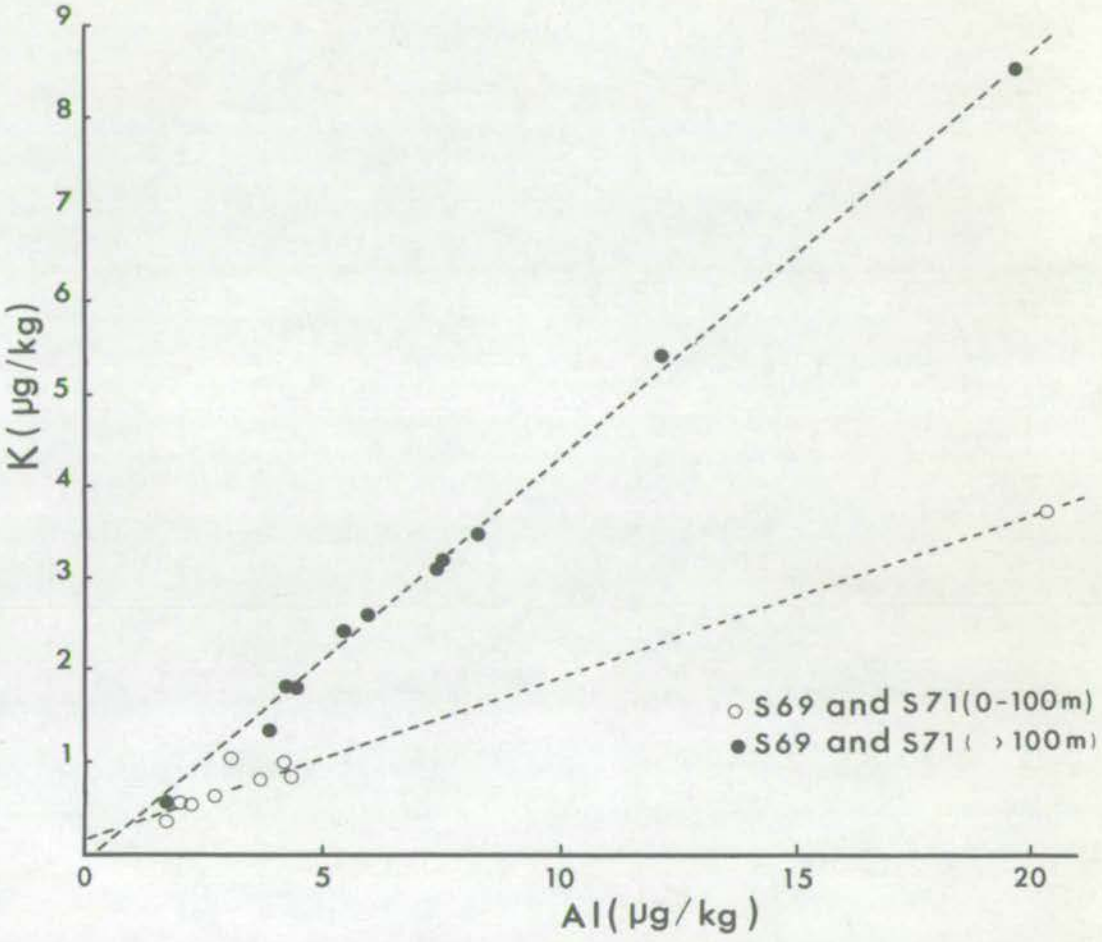


Fig. 5. 5. The K-Al relationship in particulate matter in April 1974.

associated with the clay content of the particulate matter. In most waters particulate Mg concentrations are closely related to those of Al, as demonstrated in Fig. 5.4. The ratios of Mg/Al in river particulate matter and bottom sediments are lower than those of the particulate matter in the fjord waters (Fig. 5.4). This is presumably caused by a greater contribution of non-clay aluminous material in the river input and sediments, relative to that suspended in the fjord water.

The relationship between Mg and Al varies at different periods of sampling (Table 5.1). The most pronounced change is seen in September 1973 when the particulate matter displayed very high Mg/Al ratios, particularly in the upper waters. At this time it has been demonstrated that large scale inflows of coastal water took place at shallow depths (3.7) and may have introduced suspended matter of higher Mg/Al ratio into the fjord.

The relationship between Ti and Al for station S 36-40 is demonstrated in Fig. 5.4 and Ti/Al ratios for all samples collected are shown in Table D 7, Appendix D. A strong covariance between the two elements is apparent. Ti/Al ratios in river suspended matter and bottom sediments are significantly higher than those of the particulate matter of the fjord (Fig. 5.4). As river waters, especially the river Opo, are thought to support a coarser-grained detritus as may be evidenced by high K/Al ratios (p. 67), such high Ti/Al ratios may also be related to coarse-grained particulate matter. In this respect, changes in Ti/Al ratios in particulate matter conform to its change with grainsize in sediments (Hirst, 1962).

Some higher Ti/Al ratios also coincide with high biogenous Si (p. 72). This may suggest that some Ti is associated with skeletal planktonic matter. The association between Ti and biogenic matter is more obvious in the data from April 1974, when the productivity in surface waters was high, particularly in Hardangerfjorden (see Price and Skei, 1975, Appendix E).

The interelement relationships of K, Mg, Ti and Al in waters of Hardangerfjorden differ in some respects from those observed in Sörfjorden (Table 5.1). K/Al and Mg/Al ratios in particulate matter are invariably higher in Hardangerfjorden than in Sörfjorden. There are several possible explanations for this trend. The mineralogical composition of the source material may be somewhat different and/or the grain size of the particulate matter residing in the water could vary areally. Such a trend could also be associated with a greater contribution of K and Mg residing in plankton (p. 62) in waters of Hardangerfjorden, where the productivity is higher (p. 73). However, until a more exhaustive examination is made of the influence of mineralogy, grain size and biological factors on the composition of particulate matter, the interelement relationships of K, Mg, Ti and Al are difficult to interpret.

CHAPTER 6

PARTICULATE BIOGENOUS CONSTITUENTS

Particulate biogenous matter consists of skeletal and organic constituents. The elements principally associated with these, i.e. Si, Ca, P and S, predominate either in skeletal matter (Si and Ca) or in organic matter (P and S). Si and Ca may also reside in inorganic matter; at times the former is held exclusively in particulate alumino-silicates. It will also be seen (p. 75) that particulate Ca, P and S occur as industrial contaminants in the southernmost part of the fjord.

6.1. Biogenous Si

It is difficult to assess the concentration of biogenous particulate Si accurately, as the chemical analyses (Table D 5, Appendix D) reveal only the total content of Si. The Si/Al ratios observed in particulate matter of river waters draining into Sörfjorden average 2.2. Such values are considerably lower than those of Quaternary clays from south Norway (Si/Al $\sim$2.77) and those observed in Sörfjord sediments (Si/Al $\sim$3-5). As the river-suspended matter contains no detectable quartz (5.2), in contrast to those sediments referred to above, it is assumed that the average Si/Al ratio in the detrital alumino-silicates transported into Sörfjorden is approximately 2.2. This value has been used in this study to denote detrital silicates in the fjord. Concentrations of Si in excess of a Si/Al ratio of 2.2 as a consequence, are attributed

to biogenous Si. Conversely when the Si/Al ratio is less than 2.2, the 'excess' Al is attributed to the presence of Al discharged by industry (2.2). Upon this reasoning the calculated amounts of biogenous Si in the water as given in Table D 6, Appendix D, may be regarded as minimum values.

Depth profiles of particulate biogenous Si for stations S 36, S 59 and S 71 in the middle of Sörfjorden at different times of sampling are shown in Fig. 6.1. These reveal large seasonal variations which are probably associated with seasonal changes in the production of diatoms. The most dominant diatom in the area, Skeletonema costatum (Fig. 6.2) exhibits a pronounced late autumn bloom (October/November) and an early spring bloom (February/March) (Braarud et al., 1974). Braarud et al. (1974) have also observed a small increase in the diatom population in the middle of summer, the number of diatoms becoming very small towards early autumn. The seasonal changes in the quantities of suspended biogenous Si in the water seem to be related to the concentrations of nutrient Si (Fig. 3.6) indicating an inverse relationship. For instance, in September 1973 nutrient Si is abundant in the euphotic layer while particulate biogenous Si is very low. The difference in the abundance of diatoms in the water during September 1973 and April 1974 is also evident from microscopic studies of the particulate matter.

The areal distribution of biogenous Si always displays a seaward increase (Table D 6, Appendix D). This feature may relate to the corresponding increase of inorganic detritus in the

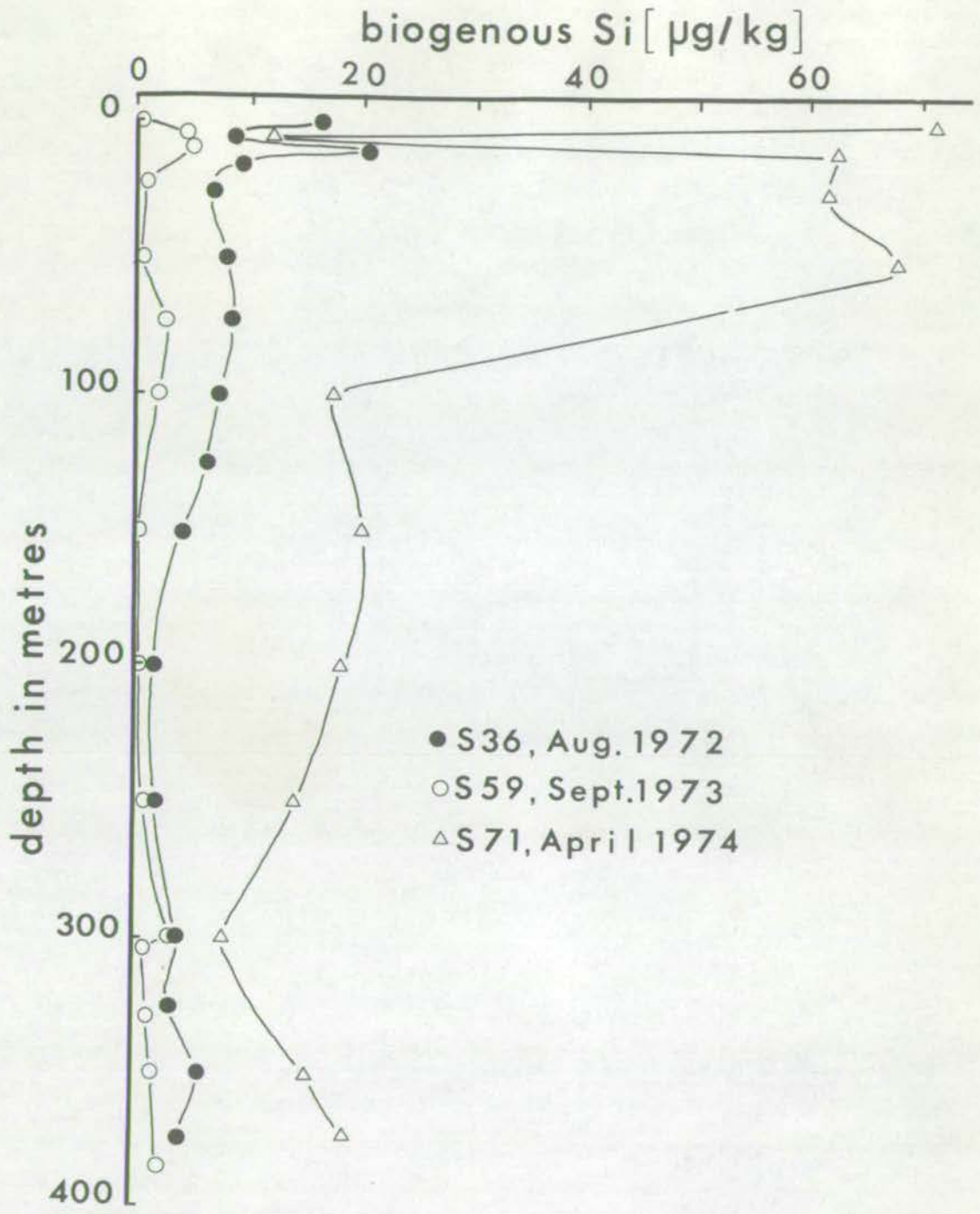
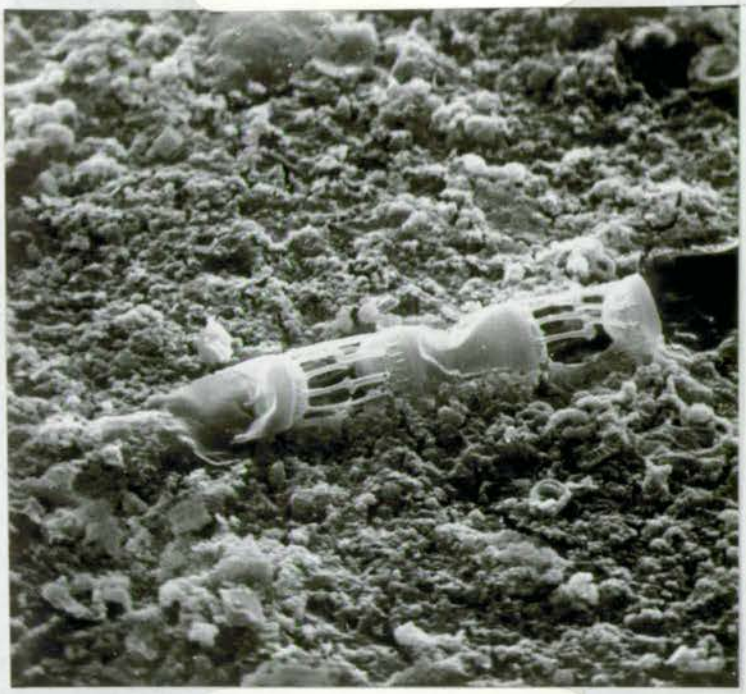


Fig. 6.1. Seasonal variations in the vertical distribution of particulate biogenous Si in the middle of Sörfjorden.

Fig. 6.2. Photomicrographs (SEM) of suspended particulate matter.

S 63 - 80 m



45 x 45 μ

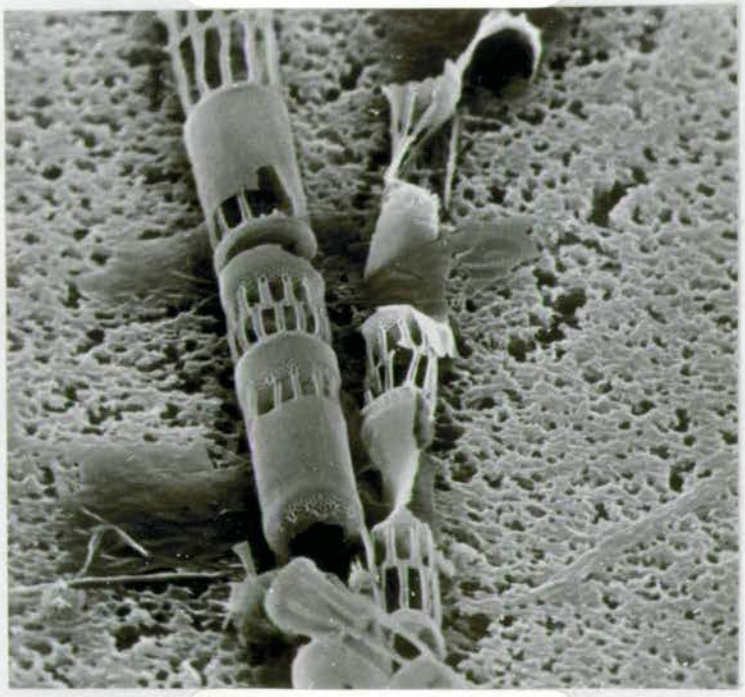
S 71 - 375 m

90 x 90 μ

S 71 - 150 m

180 x 180 μ

S 71 - 150 m

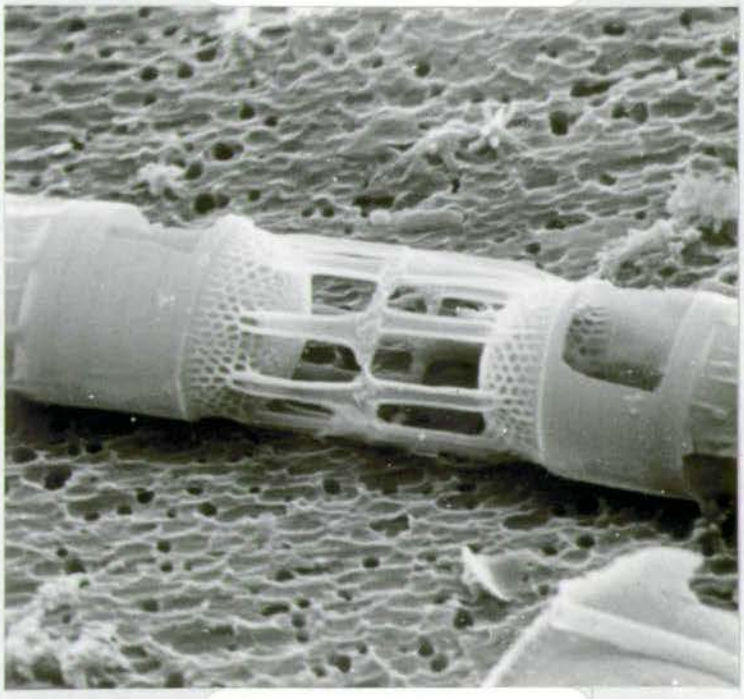


45 x 45 μ

S 70 - 750 m

90 x 90 μ

S 70 - 750 m



18 x 18 μ

surface water towards the head of the fjord, thereby reducing the light penetration in the water and retarding photosynthetic activity.

Below 200 m depth the vertical gradients of biogenous Si are small, implying that Si residing in sinking skeletal matter undergoes only minor changes in the deep water (see Riley, 1951). This is also confirmed by the microphotographs shown in Fig. 6.2, displaying well preserved skeletons of Skeletonema costatum at 750 m depth of water in Hardangerfjorden.

The Si/Al ratios in the underlaying sediments are high (3-5) partly due to the presence of much quartz (4.2) and presumably due to some initial incorporation of diatom frustules.

6.2. Biogenous Ca

Several problems arise when attempts are made to quantify biogenous Ca in the particulate matter. The Ca/Al ratios in non-calcareous sediments are variable, making it difficult to assess precisely the composition of material entering the fjord. Ca/Al ratios in river/lake suspended matter from the southern area of the fjord are low, ranging between 0.06 and 0.17. Particulate matter in two rivers draining the northern area of the fjord (with high feldspar and amphibole content, p. 61) display higher Ca/Al ratios (0.40-0.47). For this reason no attempt has been made to quantify the concentrations of biogenous Ca by determining the excess Ca over that held in alumino-silicates. Instead changes in Ca/Al ratios will be used to illustrate areal and seasonal variations, with the supposition that these may illustrate something of the behaviour of biogenous Ca in the water. This assumption, however, may be

obscured by the fact that the particulate matter of Sörfjorden contains Ca of industrial origin (2. 2) in addition to that situated in alumino-silicates and biogenous carbonate. Hence, to demonstrate seasonal and vertical changes in biogenous Ca we will consider water profiles in Hardangerfjorden. Here the amounts of particulate alumino-silicates are very low and the influence of 'industrial Ca' is thought negligible.

Fig. 6. 3 shows profiles of Ca/Al for stations H 35, H 65 and H 70 sampled at different seasons in Hardangerfjorden. A seasonal or sequential change both at the surface and at depth is apparent. Biogenous Ca seems to be most abundant in the upper 50 m, especially in September 1973. At this time values are consistently high at all depths. In this respect the seasonal changes of biogenous Ca are different from biogenous Si (p. 72) due to seasonal cycles in the plankton composition. Braarud et al. (1974) have shown Coccolithus huxleyi to be the dominant calcareous plankton species in this area. In contrast to diatoms, C. huxleyi occurs in large quantities in September ($\sim 2 \times 10^6$ cells/l) and appears associated with the annual shallow inflow of coastal water (Braarud et al., op. cit.) (p. 33). As this inflow also penetrates into Sörfjorden it is assumed that biogenous Ca is responsible for the overall higher Ca/Al ratios observed in suspended matter of Sörfjorden in September 1973.

Particulate matter from the southernmost part of Sörfjorden shows very high Ca/Al ratios at all times, except in August 1972 (see below). It seems certain that here the particulate

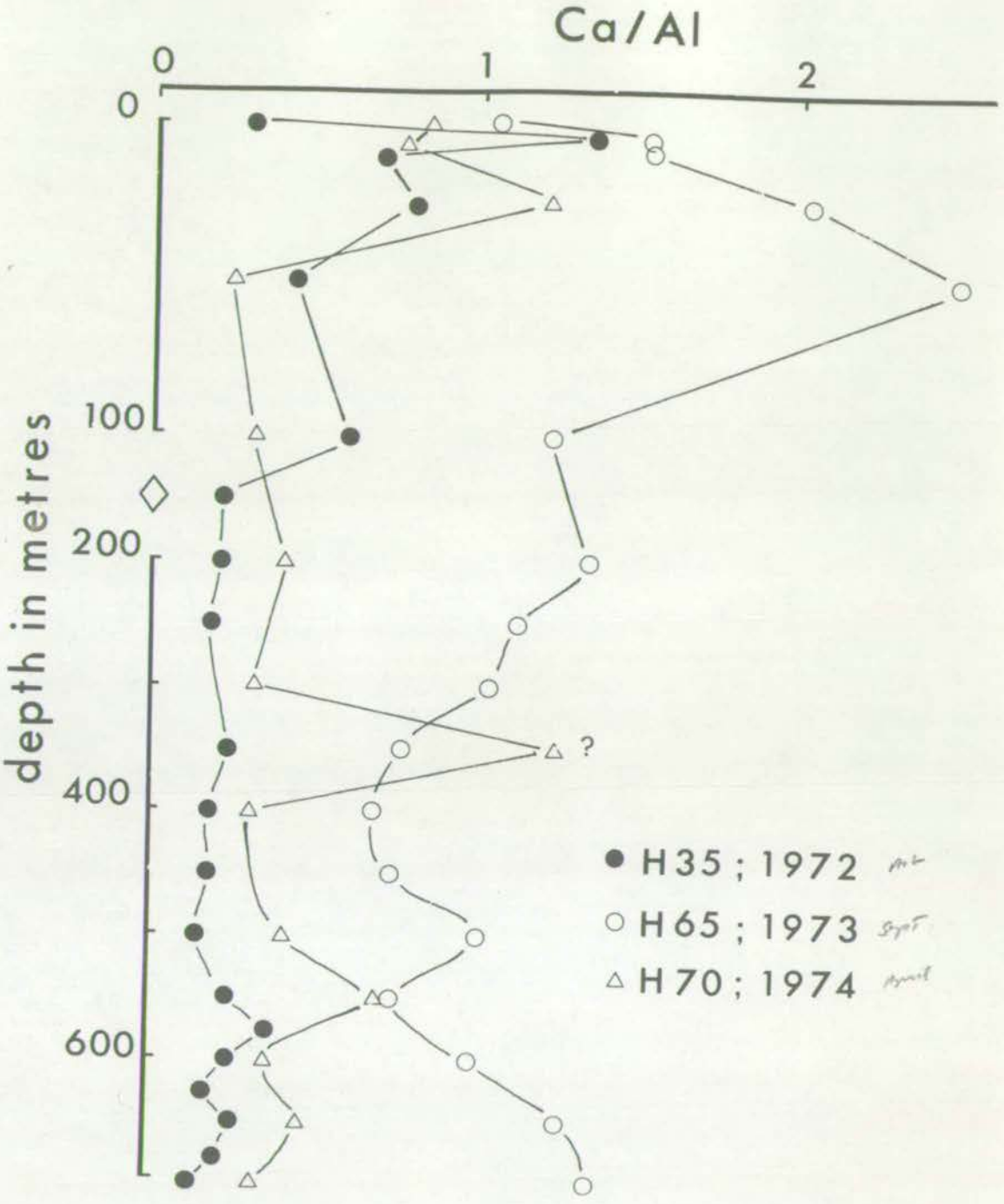


Fig. 6.3. Variations in the vertical distributions of Ca/Al ratios in particulate matter in Hardangerfjorden at different times of sampling (note change in depth scale).

matter is influenced by industrial Ca. A S.E.M. photograph (Fig. 6.2) of a sample of very high Ca/Al ratio (S 63 - 80 m) shows no coccolithophorids, and the Ca appears to be inorganic, possibly occurring in what is thought to be rhombs or prisms of calcite or gypsum.

In the Report from the Environmental Committee of Odda (1973), the authors suggest that the daily discharge of gypsum (490 tons) may dissolve and as a consequence cause precipitation of $CaCO_3$ in the water due to the supersaturation of Ca (K_{CaCO_3} 6×10^{-5}, Riley and Chester (1971)). The effects of industrial discharge of gypsum into marine waters have been studied by Sheahan (1971), who has suggested that gypsum particles flocculate along with clays. This suggestion implies that the gypsum discharged at a depth corresponding to the compensating current may be transported towards the head of the fjord, where a considerable sedimentation of Ca occurs (Fig. 4.5) being deposited either as gypsum-clay flocs and/or as precipitated $CaCO_3$ (4.2). The high solubility product of $CaSO_4 . 2H_2O$ in seawater presumably prevents its preservation in the sediments. Schaffer (1967) showed this solubility product to be 1.57×10^{-3} in seawater of normal temperature and demonstrated its increase under conditions of increasing salinity. His measurements show that 6.8 g of gypsum dissolve in 1 l of normal salinity seawater. Extrapolation of these data reveals that approximately 10^8 l of seawater is required to dissolve the daily discharge of gypsum. The efficiency of dispersing discharged gypsum, and more precisely its products of solubility (Ca^{2+}, SO_4^{2-}) from Odda

will depend very much on the water circulation, particularly the rate of water exchange. The deep surface outflow during high runoff (August 1972) may create a situation where discharged gypsum is flushed quickly out of the fjord; hence no precipitation of $CaCO_3$ is likely to occur. Precipitation of $CaCO_3$ may at times be enhanced by the photosynthetic reduction of CO_2 in the euphotic layer; a daily discharge of $CaCO_3$ (155 tons) from the industry may nucleate this precipitation.

6.3 Particulate P and S

As P and S are present in negligible amounts in clays, we can assume that their concentrations in particulate matter represent either authigenic non-silicates, or more importantly organic matter. Before any discussion of results of these elements it should be emphasized that the preparational procedures for the samples prior to analysis were different for the various cruises. Particulate matter collected in 1971, 1972 and 1973 was washed in distilled water immediately after filtering while the samples were still wet. Only in 1974 were samples left unwashed and analysed in this state. It has been found that washing immediately after filtering causes a small loss of P from the samples* (~5%, Holmes, pers. comm.). Hence, while the results of P analyses at different times of collection are not truly comparable, they do demonstrate

---

* Such a loss must not be confused with a much more serious loss (~50-70%) that takes place after washing of dried particulate matter (see Table 6.1). The results of such washing are discussed in detail in Price and Skei, 1975 (Appendix E).

Table 6.1. Percent removal of P, Mn, Pb and Zn from particulate matter by washing.

Cruise, station and date	Depth (m)	%P	%Mn	%Pb	%Zn
S 69	0	64	89	74	77
Apr 1974	5	56	77	78	52
	25	70	87	83	88
	50	51	43	69	22
	100	40	34	41	53
	200	-	43	75	55
	250	45	18	78	33
	300	32	25	59	17
	340	27	24	53	7
S 71	0	31	21	68	31
Apr 1974	5	59	75	80	53
	10	66	76	52	41
	25	63	65	79	38
	50	41	55	67	28
	100	34	27	57	43
	150	34	20	61	3
	200	40	25	66	28
	250	26	19	42	0
	300	26	10	55	26
	350	26	2	81	17
	375	33	13	86	21
S 72	0	15	24	61	21
Apr 1974	5	41	24	23	32
	10	61	64	64	39
	25	65	73	68	37
	50	26	52	64	22
	100	13	23	62	20
	110	20	23	63	21
S 73	0	18	23	61	14
Apr 1974					

variations at any one period of sampling and permit some discussion on its geochemistry. The fate of particulate S upon washing is not known.

The behaviour of P and S in particulate matter will be looked at in waters of two areas; 1) Hardangerfjorden where these elements are assumed to reside exclusively in biogenic matter and 2) the southernmost part of Sörfjorden where these elements appear to predominate in a pollutant phase.

The variations of particulate P with respect to season and depth are displayed in Fig. 6.4 for the same stations as shown in Fig. 6.3. Below 100 m there is little variation and the concentrations of particulate P are consistently low. This feature is probably associated with the decomposition processes of planktonic matter and the regeneration of nutrient phosphate (Grill and Richards, 1964). Menzel and Ryther (1964) have characterized P as an element of 'living' organic matter, hence it is mainly confined to the upper active layer.

There is a pronounced seasonal change in P in the upper 50 m (Fig. 6.4) following the trend of biogenous Si (Fig. 6.1, see also Fig. 4 in Price and Skei, 1975, Appendix E). This may imply that P is more closely associated with siliceous plankton (diatoms) than with calcareous plankton (coccolithophorids) and may reflect the difference in organic matter content in these two species.

Both P and S are linked to a common phase in particulate matter as evidenced by the covariance of the two elements in most waters of Hardangerfjorden. However due to the unknown affect

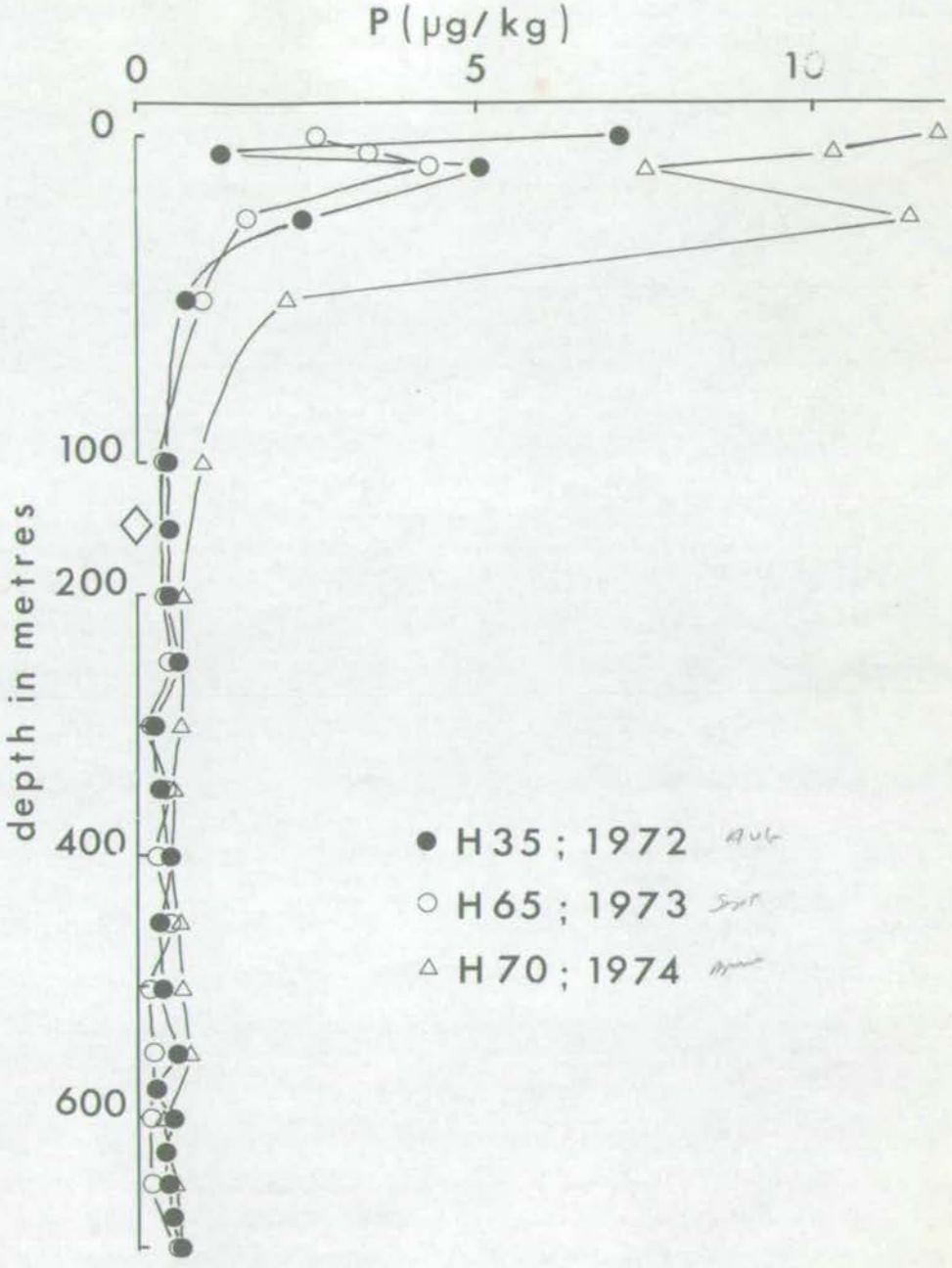


Fig. 6.4. Variations in the vertical distribution of particulate P in Hardangerfjorden at different times of sampling (note change in depth scale).

which washing with distilled water has upon "organically-bound" S , it is difficult to interpret variations in its concentration. Generally the P/S ratios in the particulate matter of Hardangerfjorden vary between 0.2 and 1.0, within the range of that in river water particulates. Some higher ratios are observed in the upper 50 m during September 1973 and especially in April 1974.

Microscopic studies showed that particulate matter collected in the southernmost waters of Sörfjorden contains much less plankton debris than samples collected further north. Hence an increase of particulate P and S in these waters cannot be attributed to an increase in productivity. Consequently their high concentrations must be associated with organic matter derived from sewage discharged from Odda, authigenic inorganic phases or direct release of industrial waste containing P and S.

Samples collected in August 1971 from the harbour area of Odda contain high concentrations of particulate P and S (Table D 5, Appendix D). At most stations a maximum of P and S occurs at 5 m depth. This maximum does not coincide with the depth of maximum concentrations of alumino-silicates (5.4) but conforms more closely to the position of the halocline (see Fig. 2 in Skei et al., 1973, Appendix E). This may be due to flocculation of colloidal humic materials at the fresh water-seawater interface (Siegel, 1971). It has also been noted that certain particulate metals (e.g. Mn and Zn) are greatly enriched at this interface (p. 84). The relationship between P, S and Mn and the position of the halocline is clearly seen from their respective depth profiles in these southern waters (Fig. 6.5).

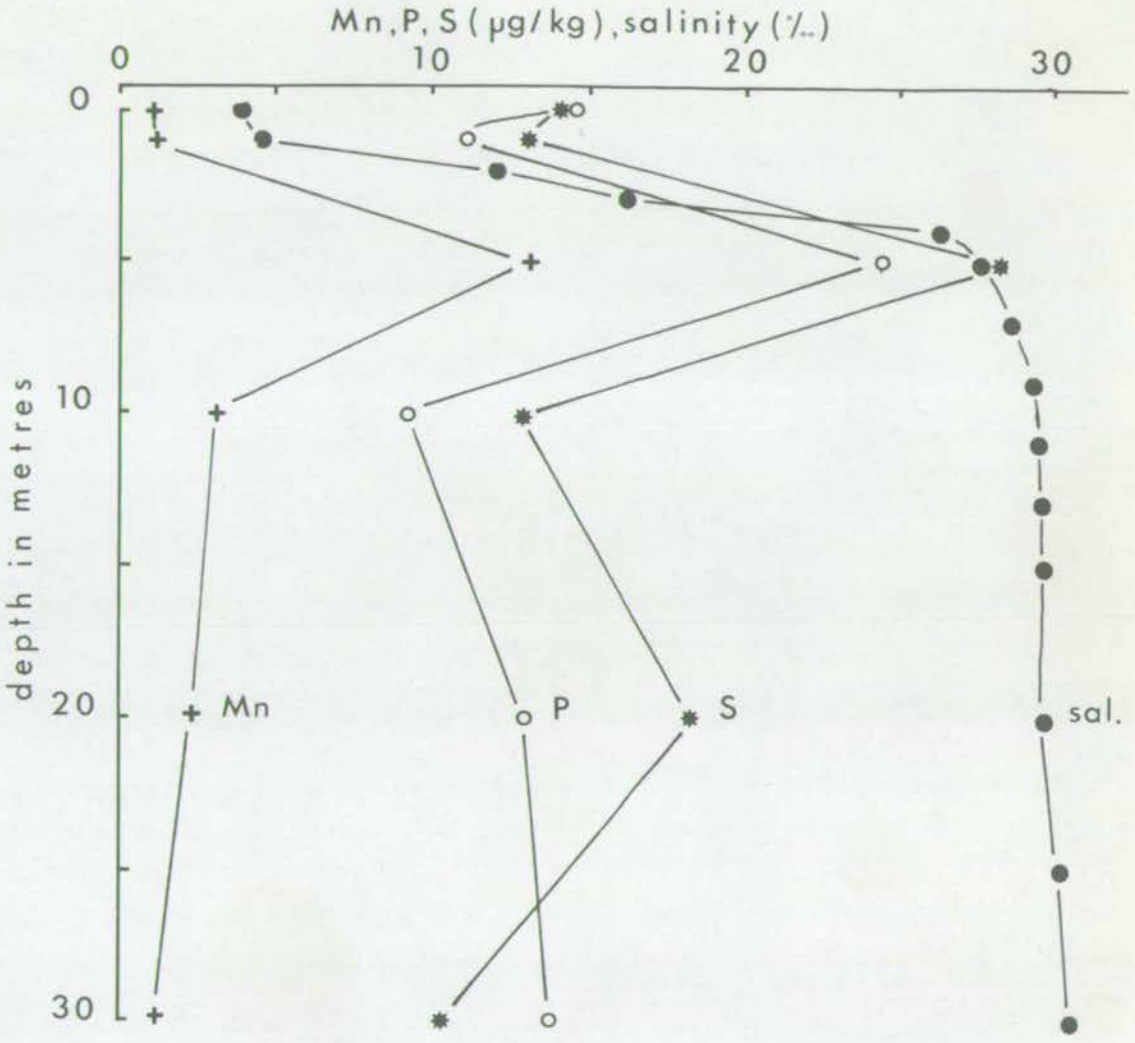


Fig. 6.5. Depth profiles of particulate P, S, non-silicate Mn and salinity at station S 27 (August 1971).

The sub-surface water in the harbour basin also contains considerable quantities of particulate P and S. Particulate S is exceptionally abundant in waters close to the zinc plant (S 28 and S 31). The same samples contain the highest concentrations of particulate Pb and Zn (p. 174) which suggests that S may be associated with these metals in the industrial waste (2. 1).

Samples collected in August 1972 all show particulate P and S concentrations to be highest in the low salinity surface waters (0 m). Below, a secondary maximum occurs at the halocline. The surface high must be associated with terrestrial input via rivers (runoff was much greater in August 1972 than August 1971). Presumably as in 1971 the high P and S at the halocline is the result of flocculation of various organic substances. In the underlaying waters concentrations of P and S decrease rapidly at depth. Some samples at intermediate depth (50-175 m) from the southern stations do not conform to this pattern and show some small increase. In such instances much of the P appears to be associated with non-silicate Fe (p. 84). This relationship is illustrated in Fig. 6. 6 and indicates a Fe/P gradient of ~3.3, similar to the ratio between "free" Fe and P in particulate matter from Loch Etive (Price and Calvert, 1973) which was attributed to the presence of ferriphosphates. Samples showing covariation between Fe and P immediately underlay or coincide with the position of high dissolved phosphate (3. 5) and high particulate non-silicate Fe (7. 2).

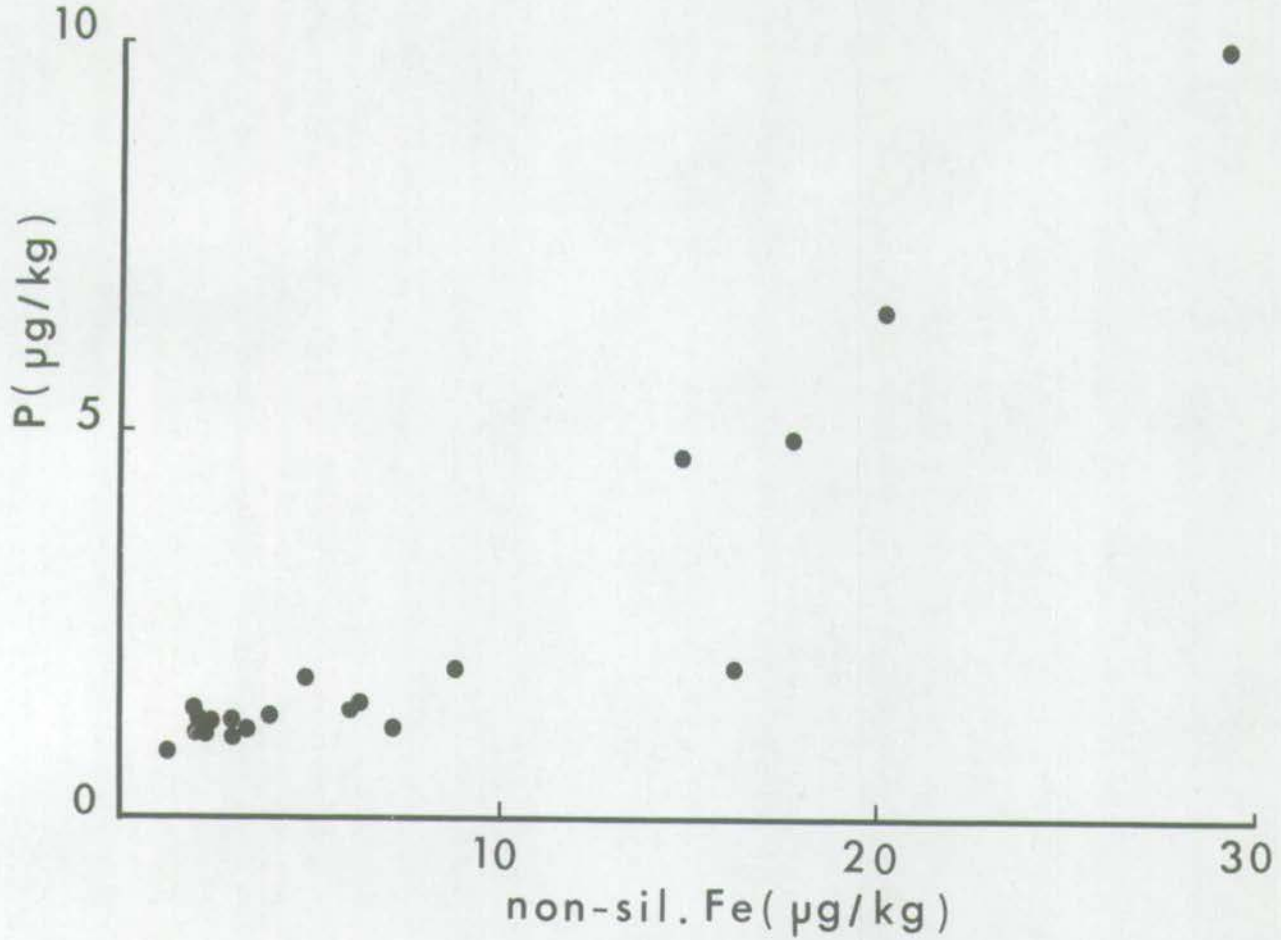


Fig. 6.6. The relationship between particulate P and non-silicate Fe at intermediate depths (50-175 m) (Fe/P gradient ~ 3.3).

CHAPTER 7

PARTICULATE AND DISSOLVED Fe AND Mn

The geochemistry of Fe and Mn in the marine environment has been thoroughly discussed by several workers in recent years. Most attention has been paid to the mobility of these elements in seawater and sediments and their transformation with respect to changes in pH and redox conditions (Piper, 1971; Nissenbaum et al., 1972; Spencer et al., 1972; Taylor, 1974).

The waters in Sörfjorden are oxygenated at all depths (3.4), hence the distribution of Fe and Mn in the water column is not controlled by redox conditions. However, changes in pH may play a role in the precipitation of Fe and Mn in some near surface waters.

The study of Fe and Mn in Sörfjorden emphasizes the partitioning of these elements between detrital alumino-silicates, organic constituents, authigenic phases and pollutants. While we have to date been considering the composition of particulate components (Chapters 5 and 6), problems concerned with Fe and Mn also involve dissolution and precipitation. Hence, the following account will be concerned with these elements in both their particulate and dissolved states.

The amount of 'excess' or non-silicate Fe in suspended matter is difficult to assess. Previous workers have adopted an arbitrary Fe/Al value ranging from 0.5 to 0.7 to represent the Fe content of silicate material (Spencer and Sachs, 1970; Price and

Calvert, 1973). However, as the terrain surrounding Sörfjorden is predominantly gneissic (p. 6) and analyses of pre-Cambrian gneisses from other parts of Norway show a Fe/Al ratio of ~0.2 (e.g. Rutland and Sutherland, 1967), the above range of values could be unrepresentative of the silicate input. In Fig. 7.1 the distribution of non-silicate Fe at station S 59, based on Fe/Al ratios ranging from 0.2-0.7, is shown. Even if we regard non-silicate Fe to be Fe held in excess of Al in a Fe/Al ratio of either 0.2 or 0.7, the respective results do not alter to any obvious degree the trend in non-silicate Fe with depth for this profile (Fig. 7.1). Hence, as a compromise, a Fe/Al ratio of 0.5 has been adopted to express the concentration of silicate Fe in all particulate matter. Any Fe held in excess of a ratio with Al of 0.5 will be termed non-silicate Fe.

Manganese is associated with detrital silicates to a lesser extent than Fe (Goldschmidt, 1954) (see also Fig. 7.2). The average Mn/Al ratio in Sörfjord sediments (~0.013) is similar to that of Quaternary clays (Roaldset, 1972). Hence, Mn in excess of a Mn/Al ratio of 0.01 is taken to represent non-silicate Mn.

7.1. Particulate and dissolved Fe and Mn in river/lake waters

Rivers transport Fe and Mn in particulate and dissolved forms (Nesterova, 1960; Stumm and Morgan, 1970). The results of analyses in Table D 5, Appendix D, show that in the river Opo 95% and 54% of the total Fe and Mn respectively are transported as solids (>0.45μ). The pronounced difference between Fe and Mn reflects their relative abundance in alumino-silicates. Concentrations of particulate Fe in all the river and lake waters

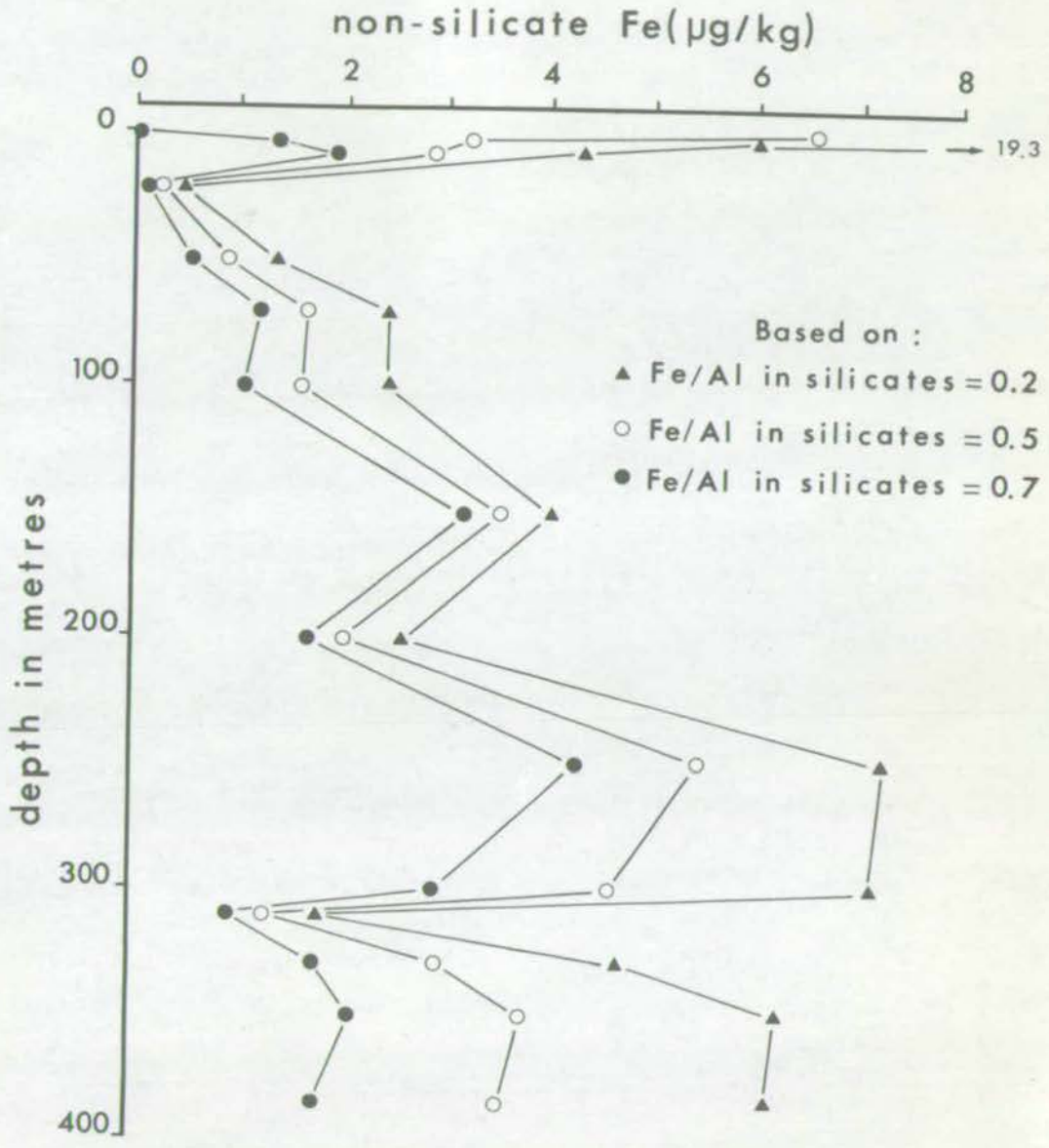


Fig. 7.1. The distribution of particulate non-silicate Fe at S 59 based on various Fe/Al ratios in alumino-silicates.

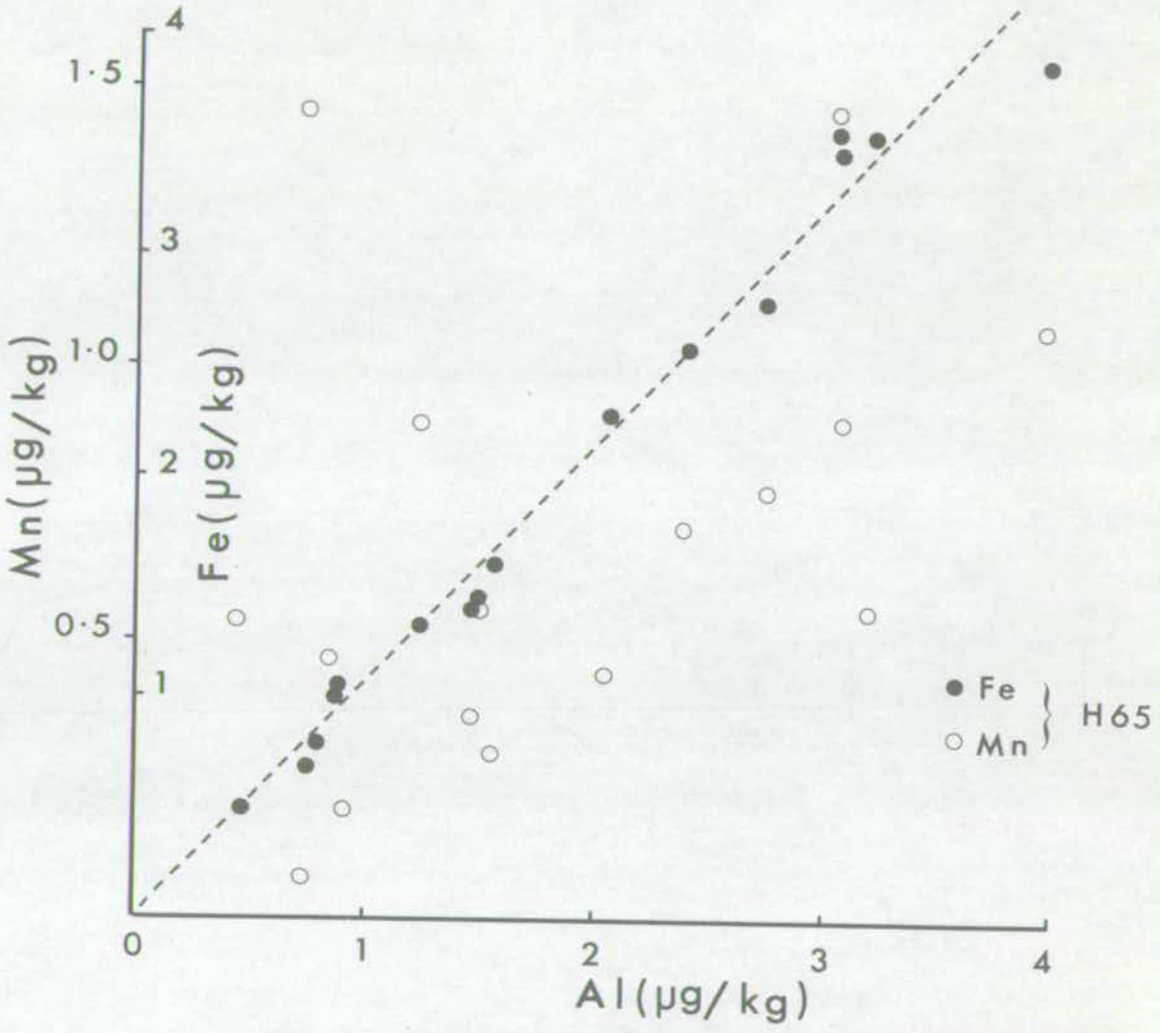


Fig. 7.2. The relationship between Fe, Mn and Al in particulate matter.

(Table D 5, Appendix D) vary between 11.26 and 677.2 µg/kg, approximately 60% being non-silicate Fe. This implies that Sörfjorden receives appreciable amounts of particulate "hydrous ferric oxide" ($Fe_2O_3 . nH_2O$) (Stumm and Morgan, 1970), and/or precipitated Fe-organic complexes (Malcolm, 1972).

Concentrations of particulate Mn for all river and lake waters are considerably less and range from 0.20 to 10.02 µg/kg. Only 15-30% of Mn residing in the particulate matter can be regarded as oxides.

As might be expected, concentrations of dissolved Fe and Mn in river/lake waters are less than those of their particulate forms and vary between 5.2 and 42.5 µg/kg and 2.4 and 7.1 µg/kg respectively (Table D 5, Appendix D). These concentrations are similar to those quoted by other workers (e.g. Taylor, 1974). The particulate non-silicate/dissolved ratios observed were ~10/1 (Fe) and ~1/10 (Mn). This discrepancy in ratios may be due to a selective precipitation of Fe relative to Mn in riverwater containing both metals (Krauskopf, 1957).

7.2. The distribution of Fe and Mn in the fjord at high runoff (August 1971/72)

The supply of non-silicate and silicate Fe via rivers induces a surface maximum of Fe in the fjord, generally decreasing northwards (Table D 5-6, Appendix D). In contrast, particulate non-silicate Mn is more abundant at the halocline, especially in the harbour area (data from August 1971, Table D 6, Appendix D), than at the surface (Fig. 6.5). The pH was measured (Appendix B) in

water samples collected in 1971. In the surface waters of the harbour basin near Odda, pH values ranged from 3.72 to 5.67. The halocline separates the low pH surface water and water of normal pH (~7.8); near the bottom pH values fall below 7.3. This anomalously low pH is associated with considerable discharge of phosphoric and sulphuric acid from the zinc plant (Environmental Committee Report, 1973). As the pronounced increase of non-silicate Mn at the halocline (Fig. 6. 5) only is observed in waters of unusual pH and its increase does not conform to the distribution of detrital matter, it is assumed that a reaction takes place at the halocline, leading to the formation of particulate Mn. Higher levels of particulate Zn are also observed in the same samples, which may indicate scavenging of metal ions by Mn (Murray, 1975). While there seems to be no anomalous increase in concentration of non-silicate Fe at or near the halocline, this does not imply a lack of precipitation of Fe(III) from river water at this boundary. The considerable input of industrial Fe(III) below the halocline and riverborne Fe(III) above the halocline would have a masking effect on its presence there. It is also evident from Fig. 6. 5 that particulate P and S conform to the pattern shown by Mn. These elements may be intimately associated with freshly precipitated Fe(III) either due to inorganic coprecipitation, adsorption or to the presence of Fe-organic flocs (Malcolm, 1972). It should also be added that waters of the extreme southern part of the fjord have an unusually high content of dissolved Fe and Mn (p. 87) as well as P (p. 24).

The lateral and vertical distributions of particulate non-silicate Fe for August 1972 are shown in Fig. 7.3. Highest non-silicate Fe occurs at the surface (0 m) and in a lobe of water situated close to the seabed in the south, extending northward to appear in lesser concentrations some 100 to 150 m from the seabed (400 m) in the middle of the fjord. Almost certainly the source of this Fe is the zinc smelting works (D.N.Z., see Fig. 1.5), which discharges Fe-waste (2.1). Because of the contamination by industrial Al in some waters (p. 62), the values of non-silicate Fe as presented must be regarded as minima. A more accurate assessment of the non-silicate Fe (Mn) could be achieved if Ti is substituted as an indicator of aluminium-silicates in these contaminated waters.

The density of the Fe-containing effluent released by the zinc plant is 1.09 g/ml (2.1), being appreciably higher than that of the surrounding seawater (1.021-1.026 g/ml). When such a suspension is introduced as a continuous effluent, it spreads downcurrent as a plume (Pritchard, 1959) initially following the seabed until mixing with seawater reduces the density sufficiently to prevent further sinking. As a consequence the suspension gradually loses its identity.

The effectiveness of the initial mechanical dilution will depend on the density difference between this effluent and the receiving seawater (Pritchard, 1959). A density difference of ~ 0.07 g/ml will inhibit both mechanical dilution as well as dispersion by turbulent diffusion. This may explain why this Fe-suspension appears to act

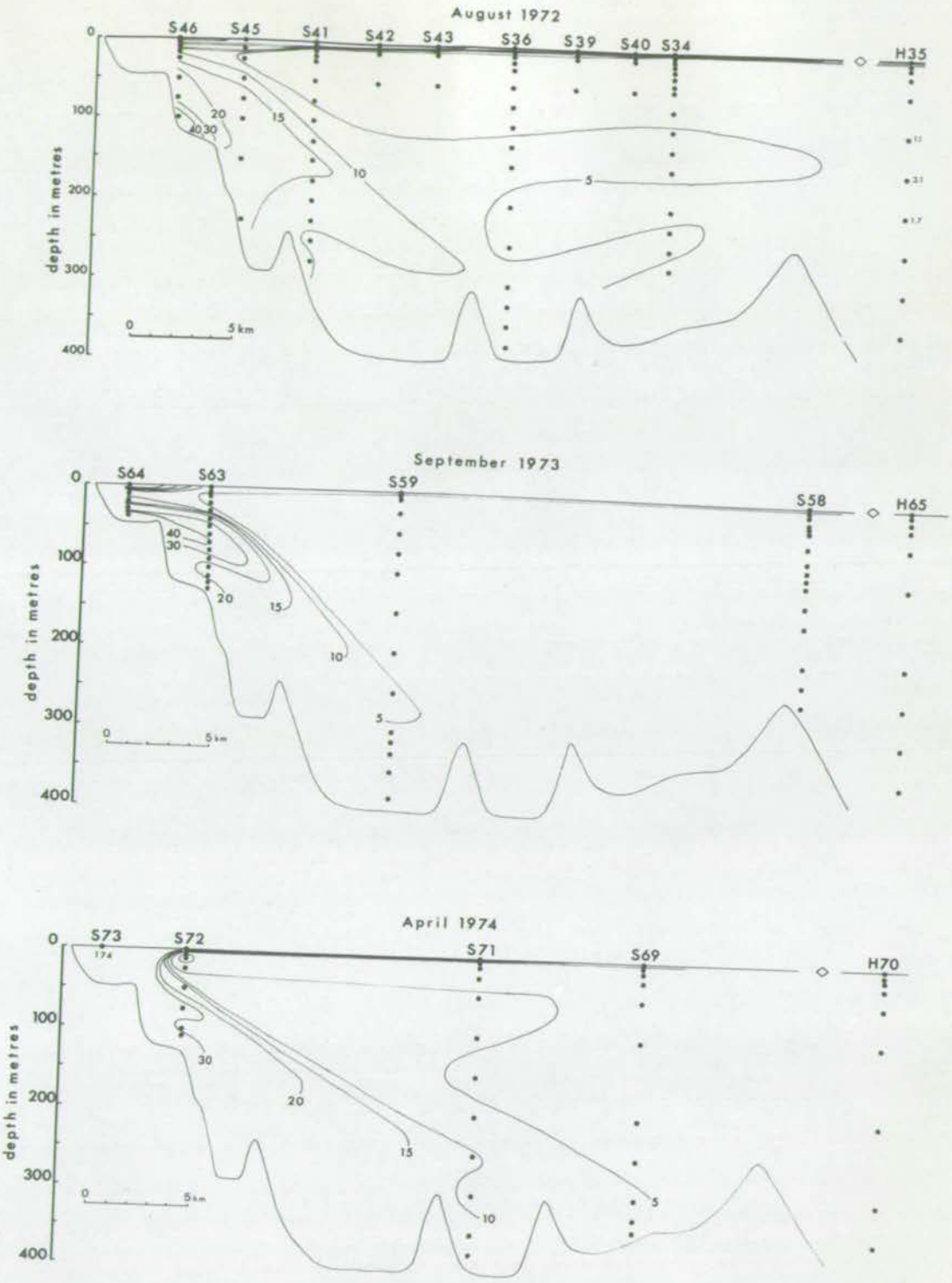


Fig. 7.3. Lateral and vertical distribution of particulate non-silicate Fe during August 1972, September 1973 and April 1974 (isopleths at 5, 10, 15, 20, 30 and 40 µg/kg).

as a gravity flow, until diluted sufficiently to be mixed into the surrounding watermasses towards the north. Another factor which prevents the contaminated plume from reaching the deepest waters of the fjord is its vertical displacement created by the momentum of inflow of deep water associated with flushing. This feature is clearly recognized in August 1972 (3.8). Similarly the tongue of water wedging into the high-Fe plume between 200 and 250 m depth (Fig. 7.3) apparently originated outside Sörfjorden.

The distribution of particulate non-silicate Mn does not conform to that of Fe, particularly in the near-surface waters. Instead, it shows a sub-surface high and a near-bottom maximum (Fig. 7.4). The high particulate Mn near the surface at stations in the southernmost part of the fjord, is presumably a result of a transformation mechanism at the halocline (p. 84). At the outlying stations higher Mn occurs at 50 m depth. It will be shown later (Chapter 9) that this Mn is associated with vertical displacement of deep water. The bottom water maximum is thought to be a consequence of resuspension of Mn-enriched surface sediments (see 4.3c and Chapter 9 for discussion).

While the distribution of non-silicate Fe and Mn as portrayed in Figs. 7.3-4 appears at first sight to be very different, a closer inspection of the depth profiles of these elements at several stations, S 36 in particular (Fig. 7.5), reveals some covariation which may be the result of the overall chemical affinity of these elements in the marine environment (Spencer et al., 1972).

The results of the analyses of dissolved Fe and Mn in

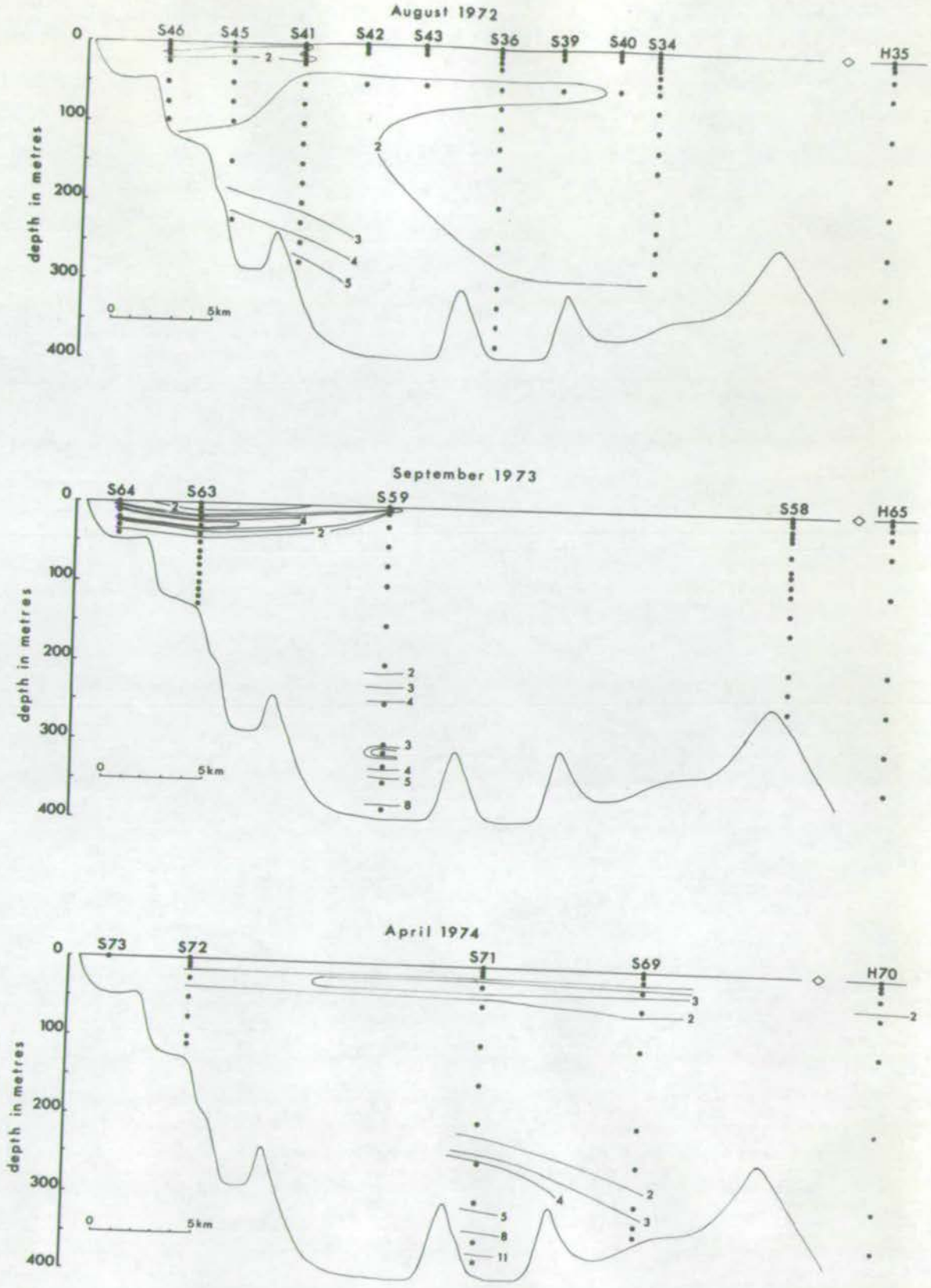


Fig. 7.4. Lateral and vertical distribution of particulate non-silicate Mn during August 1972, September 1973 and April 1974 (isoplet' : at 2, 3, 4, 5, 8 and 11 µg/kg).

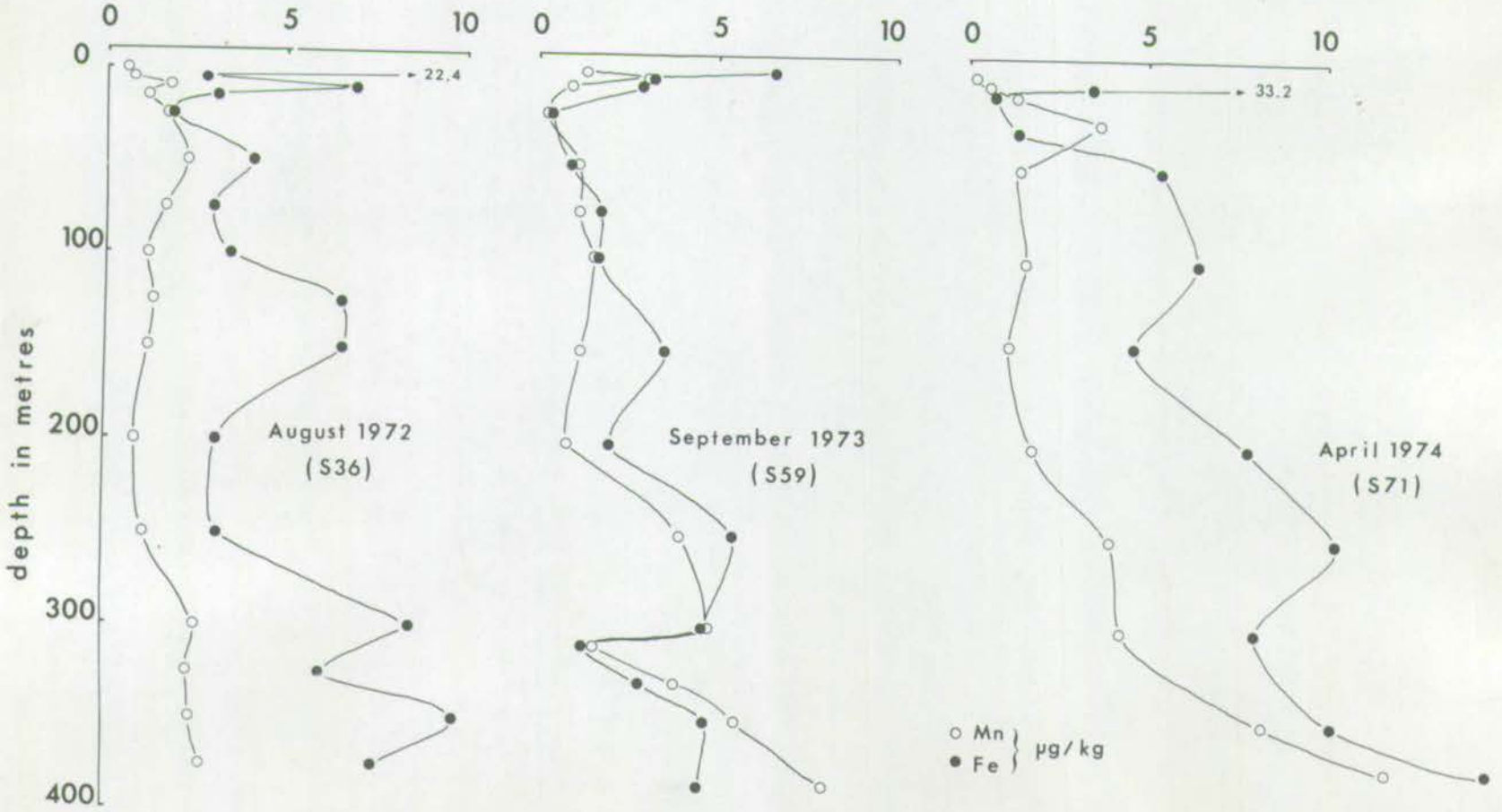


Fig. 7. 5. Vertical distribution of particulate non-silicate Fe and Mn in the middle of Sörfjorden at various cruises.

the most southern waters during August 1972 show unusually high levels of both metals in the upper 75 m (Table D 5, Appendix D). For instance, the concentration of dissolved Fe in the surface water of S 46 is ~25 times that of normal seawater (cf. Dyrssen et al., 1972). There is, however, a pronounced seaward decline of Fe, expecially in the surface; at station S 36 the Fe content is normal. This trend cannot be explained by a simple dilution of Fe-rich brackish water by entrained seawater, as the salinity in the surface water is approximately uniform (Fig. 3.2). This suggests removal of dissolved Fe, presumably by precipitation of Fe-hydroxide flocs (Coonley et al., 1971) and/or to some extent through uptake by plankton (Cooper, 1935; Lewis and Goldberg, 1954; Martin, 1970). The transformation of Fe(II) to Fe(III) in the surface water, is also supported by the increase of non-silicate particulate Fe observed in the middle of the fjord (S 42 - 0 m and S 43 - 0 m, Table D 6, Appendix D).

In the deeper waters, dissolved Fe is slightly more abundant; these values are broadly coincident with the middle of the 'effluent plume' described above (see e.g. S 45 - 150 m and S 41 - 150 m, Table D 5, Appendix D).

Maximum dissolved Mn occurs at 25 m depth and coincides with the maximum of dissolved Pb and Zn as will be seen later (Chapter 8). Its concentration increases towards the head of the fjord and at station S 46 44 µg/kg Mn was measured at 25 m depth. These anomalous Mn concentrations in the southern area may be caused by a small but significant industrial discharge (Table 2.3).

7.3. The distribution of Fe and Mn in the fjord at moderate runoff (September 1973)

During this period the amounts of suspended non-silicate (and silicate) Fe in surface waters of the fjord are reduced due to the smaller input from the rivers. In contrast, concentrations of non-silicate Mn are higher in the surface (0 m), when compared with the situation described for August 1972. Comparison of the data for stations S 36 (1972) and S 59 (1973) shows surface concentrations of non-silicate particulate Mn to be more than doubled in 1973 (Table D 6, Appendix D). Similarly, the concentrations of dissolved Mn at the same stations and the same depths (0 m) are almost doubled (Table D 5, Appendix D). As seen below and in Chapter 8 the same surface waters also display a pronounced increase in pollutant Fe, Zn and Pb. Thus it is believed that the high Mn concentrations are associated with industrial discharge.

The lateral and vertical distributions of particulate non-silicate Fe are shown in Fig. 7.3. Although the small number of samples collected provide only a very restricted picture of its distribution pattern, the general trend resembles that of August 1972. However, the concentrations of Fe in the deep water plume differ in one major respect. In September 1973, Fe is abundant in the south close to its source but shows a rapid falloff northwards (Fig. 7.3). This feature can be explained by the autumnal near-surface inflow (p. 33) which causes a pile-up of contaminants in the extreme south (p. 97).

The distribution of non-silicate Mn (Fig. 7.4) also displays many features seen in 1972, but now particulate Mn in the

near-surface waters appears to be confined to the southernmost part of the fjord and preferentially at depths between 10 and 30 m, coinciding with inflowing water. The source of this Mn and the cause of its precipitation is unclear. However, it may be a phenomenon associated with mixing between inflowing water of high pH and outflowing contaminated water of low pH (p. 84).

A pronounced increase of particulate Mn in the bottom water of the central basin of Sörfjorden is clearly observed, and appears to result from sediment disturbances (see Chapter 9).

Fig. 7. 5 shows the depth profile of non-silicate Fe and Mn at station S 59. Again some covariation is apparent (see p. 86). However the relative amounts of non-silicate Fe and Mn are widely different from those observed previously. During August 1972 (S 36), the non-silicate Fe/Mn ratio of the particulate matter varies between 2 and 5 at most depths as opposed to 0.4 and 3 in September 1973 (S 59). This discrepancy is most conspicuous below 300 m where Mn preponderates over Fe (1973).

Dissolved metals were only measured in samples collected at station S 59 in 1973. These results (Table D 5, Appendix D) show a pronounced vertical variation, especially for Mn. High dissolved Mn was found in the surface (0 m) and at 50 to 75 m. Sandwiched between these two layers were waters impoverished in dissolved Mn and presumably representing inflowing water originating primarily from outside Sörfjorden (p. 33).

7.4. The distribution of Fe and Mn in the fjord at low runoff (April 1974)

As at other times non-silicate Fe concentrations are abundant in the surface water, particularly in the southern part of the fjord (Table D 6, Appendix D). As this feature conformed to a substantial increase of particulate and dissolved pollutants (e.g. Pb and Zn) it is assumed that the primary source of the Fe at this time is industrial waste.

The vertical and areal distributions of non-silicate Fe as illustrated in Fig. 7.3 again resemble those seen in previous years.

The deep water plume, descending from the innermost basin towards the deepest parts of the fjord, is evident, as is the increase of Fe in the lowest waters, extending some 50 m above the seabed (e.g. S 71 and S 69).

The distribution of particulate non-silicate Mn is shown in Fig 7.4. There are two obvious features: 1) high Mn concentrations at 10 to 50 m depth and 2) an increase of Mn towards the sediment-water interface, particularly in the deepest basin. These features are also displayed in Fig. 7.5. The near-surface high Mn does not appear to be associated with any phenomena at the halocline as noted at other times. Instead, this Mn appears intimately associated with the biogenous matter occurring in these waters at this time (p. 78). Hence, it is assumed that much of this Mn resides in organic or less probably skeletal matter. The deep water suspended Mn seems, as in the instance of much

non-silicate Fe (see Fig. 7.3), to be coupled with considerable sediment disturbance. In contrast to September 1973, Fe preponderates over Mn in the deep water (S71, Fig. 7.5) but the non-silicate Fe/Mn ratios are invariably lower compared with August 1972 (p. 89).

Particulate matter collected in 1974 was analysed both before and after washing with distilled water. The latter analyses are thus subject to the deleterious effect that drying and subsequent washing has on the composition of particulate matter (Price and Skei, 1975, Appendix E). The percentage loss of Mn from samples collected in Sörfjorden caused by this treatment is given in Table 6.1. These results show most clearly that Mn is associated with at least two particulate matter components, that respond differently to washing. More than 50% Mn is lost from samples collected in the upper 50 m of the fjord, compared with samples from deeper waters, which suffer only a 10-30% loss. This feature is demonstrated for one depth profile (S71) in Fig. 7.6. The similarity in behaviour of Mn and P (p. 77) when subjected to washing, suggests that non-silicate Mn present in the euphotic layer predominates in biogenous matter. Morris (1971) observed an increase of particulate Mn in seawater during a plankton bloom and he attributed this to surface adsorption of Mn onto phytoplankton. A similar mechanism of adsorption of metals, including Mn, onto copepod exoskeletons has been reported by Martin (1970).

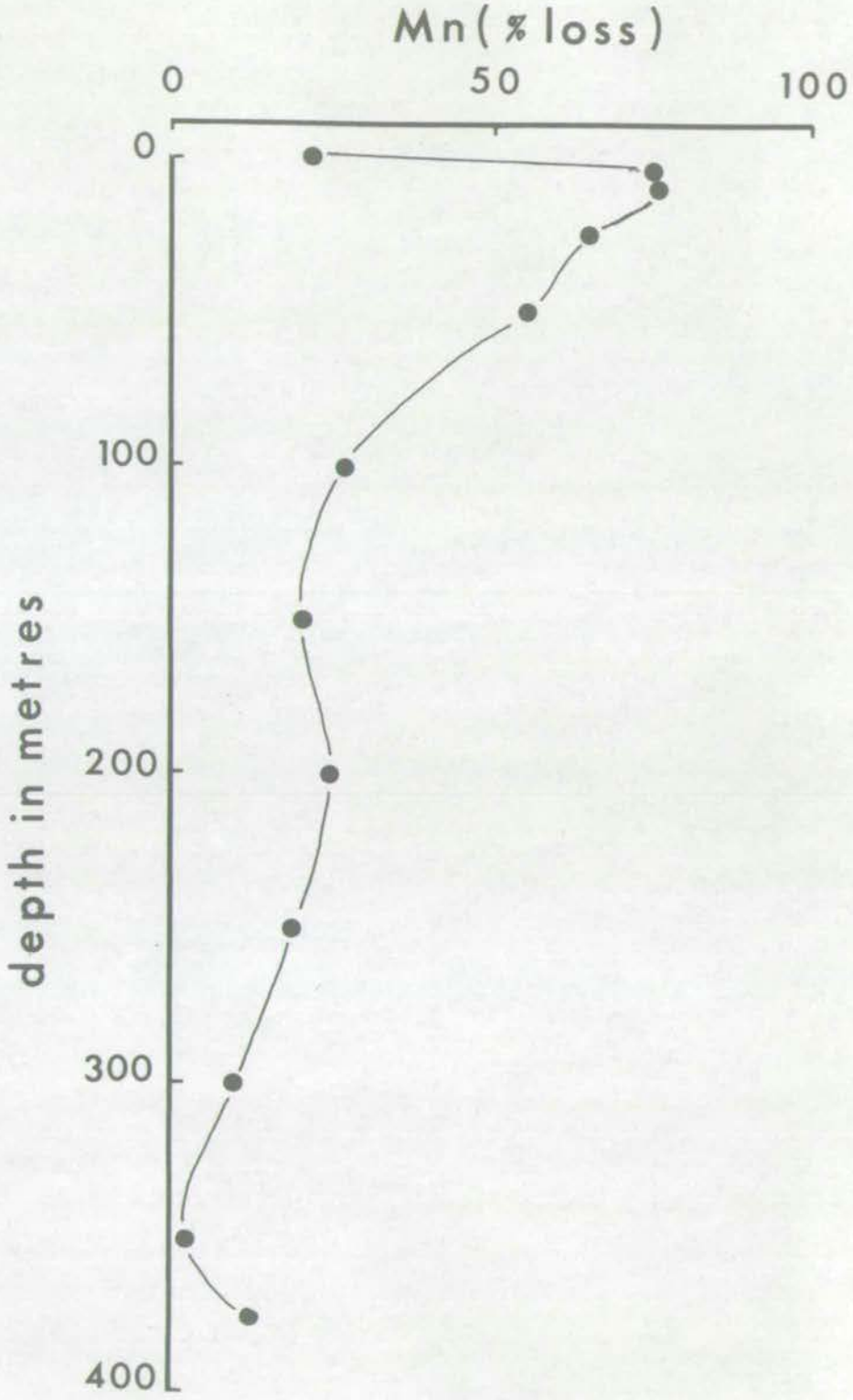


Fig. 7.6. Percentage loss of Mn from particulate matter upon washing (S 71).

In contrast to the loss of Mn from shallow water samples, particulate Mn in the deep water, which is thought to represent dispersed oxides, shows very little change during drying and washing (Table 6.1).

CHAPTER 8

PARTICULATE AND DISSOLVED Cu, Pb AND Zn IN THE WATER

Trace metals occur in normal seawater in sufficient quantities to sustain biological growth in the sea. Although some metals are essential micro-nutrients in the enzyme system of marine organisms (Zirino and Healy, 1970), it is unlikely that plankton growth is ever limited by the lack of trace metals (Riley and Chester, 1971) (cf. Boyle and Edmond, 1975). In the last decade there has been more concern about the surplus of trace metals in the oceans created by man-made sources (Goldberg, 1970). A trace metal which in normal seawater is important in sustaining life may have an inhibitory effect on marine organisms when concentrations of a particular trace metal exceed a certain threshold. This has been emphasized in several studies (Jones, 1938; Mandelli, 1969; George, 1970; Bryan, 1971; Nuzzi, 1972).

Sörfjorden is an area where the local discharge of heavy metals is sufficiently high to cause concern about the marine life. Hence, an attempt was made to study the distribution of three heavy metals; Cu, Pb and Zn in particulate and dissolved state in the watermasses, to gain some knowledge about the behaviour, transport and dispersal of these metals in the fjord.

8.1. Cu, Pb and Zn in river/lake waters

The concentrations of particulate and dissolved Cu, Pb and Zn in river/lake waters from the area about Sörfjorden are shown in Table 8.1, along with results from other studies.

Table 8.1. Metals in river water (μg/kg)

	Cu		Pb		Zn	
	diss	part	diss	part	diss	part
River Fossa	-	-	-	0.3	-	0.4
River Opo (average upper and lower)	3.4	-	-	3.2	15.0	1.8
Lake Ringdalsvann	2.2	-	-	0.4	15.3	0.3
River Espe and Ullensvang (average)	4.5	-	-	1.6	25.7	1.0
Turekian (1969)[1]	7	-	-	-	20	-
Taylor (1974)[2]	0.5-0.8	-	-	-	5.2-9.6	-

1 Average world value for rivers.
2 Rivers Moelv, Beitleelv and Vosso, West Norway.

The concentrations of dissolved Cu and Zn, although broadly comparable with values quoted by other workers, tend to be higher than levels found in other rivers of West Norway (Taylor, 1974).

The levels of particulate Pb and Zn in the riverwater are appreciably higher relative to Al than those observed in 'unpolluted' sediments from Sörfjorden. The Pb/Al and Zn/Al ratios in the river particulates from River Opo are $\sim 60 \times 10^{-4}$ and $\sim 35 \times 10^{-4}$ respectively; the corresponding ratios in sub-surface sediments from Sörfjorden are $\sim 4 \times 10^{-4}$ and $\sim 20 \times 10^{-4}$. The quantity of Zn relative to Al may be compared with data of Spencer and Sachs

(1970) which showed a linear relationship and a Zn/Al ratio of 18×10^{-4} in the bottom waters of the Gulf of Maine. This ratio has been considered to represent that of alumino-silicates. The higher Pb/Al and Zn/Al ratios in particulate matter and dissolved Cu and Zn in river Opo may well be due to the contribution of local atmospheric fallout of metals in the catchment area of the river. Measurements of the monthly fallout of Pb and Zn in the vicinity of the industrial plants near Odda showed values of 6.6 mg/m^2 and 177.8 mg/m^2 respectively (Environmental Committee Report, 1973). In contrast, measurements of fallout of the same metals in a less industrialized area in England showed a monthly fallout of 4.5 mg/m^2 Pb and 10 mg/m^2 Zn (Pierson et al., 1973).

8.2. Suspended particulate Cu, Pb and Zn in waters of Sörfjorden at various seasons

The results of the analyses of particulate Cu, Pb and Zn in samples collected in 1971 are reported in Skei et al. (1973) (Appendix E) and will not be discussed here.

The distributions of particulate Cu and Zn in the water in August 1972 (Table D 5, Appendix D) are very similar and display pronounced maxima at the surface (0 m) and a general increase towards the southernmost stations. Maximum concentrations of Zn and Cu in these waters are 6.6 µg/kg and 5.4 µg/kg respectively. At depth their concentrations are lower and erratic. It seems that except for local enrichments of particulate Cu and Zn in the south, their concentrations in Sörfjorden during August 1972 are not very much higher than those measured in coastal waters (Slowey and

Hood, 1971; Preston et al., 1972) and in Hardangerfjorden (Price and Skei, 1975).

The concentration range of particulate Pb in samples collected during this period is <0.1 to 10.04 µg/kg (Table D 5, Appendix D). The lateral and vertical distribution (Fig. 8.1) shows, as noted with Cu and Zn, high concentrations in the surface water but additionally it displays high concentrations in waters of 25 m to 150 m depth. As coastal waters contain total Pb concentrations between 0.6 and 2.9 µg/kg (Preston et al., 1972) it would appear that industrial Pb is contaminating Sörfjorden. Fig. 8.1 indicates that an outflow of metal-contaminated water occurs at two depths; that is at the surface and at intermediate depths (25-150 m). However, metals released and carried expecially in the surface water need not have been originally in particulate form, but could have been sorbed onto, or incorporated into solid matter during their travel. The persistence of Pb at intermediate depths from Odda to Hardangerfjorden (H 35) suggests that Pb in particulate form is not easily removed from the waters of Sörfjorden. Furthermore, it should be noted that the bulk of Pb and Zn is not associated with the deep water plume of Fe-waste (Fig. 7.3) that occurs during this and subsequent periods of sampling, despite the fact that 100% of Pb and 60% of Zn reside in the jarosite residue discharged from the zinc plant (Table 2.1). However, Fig. 8.1 indicates that some Pb is coupled with the Fe-waste in the water.

The analyses of particulate metals in samples collected in September 1973 provide evidence of greater metal contamination,

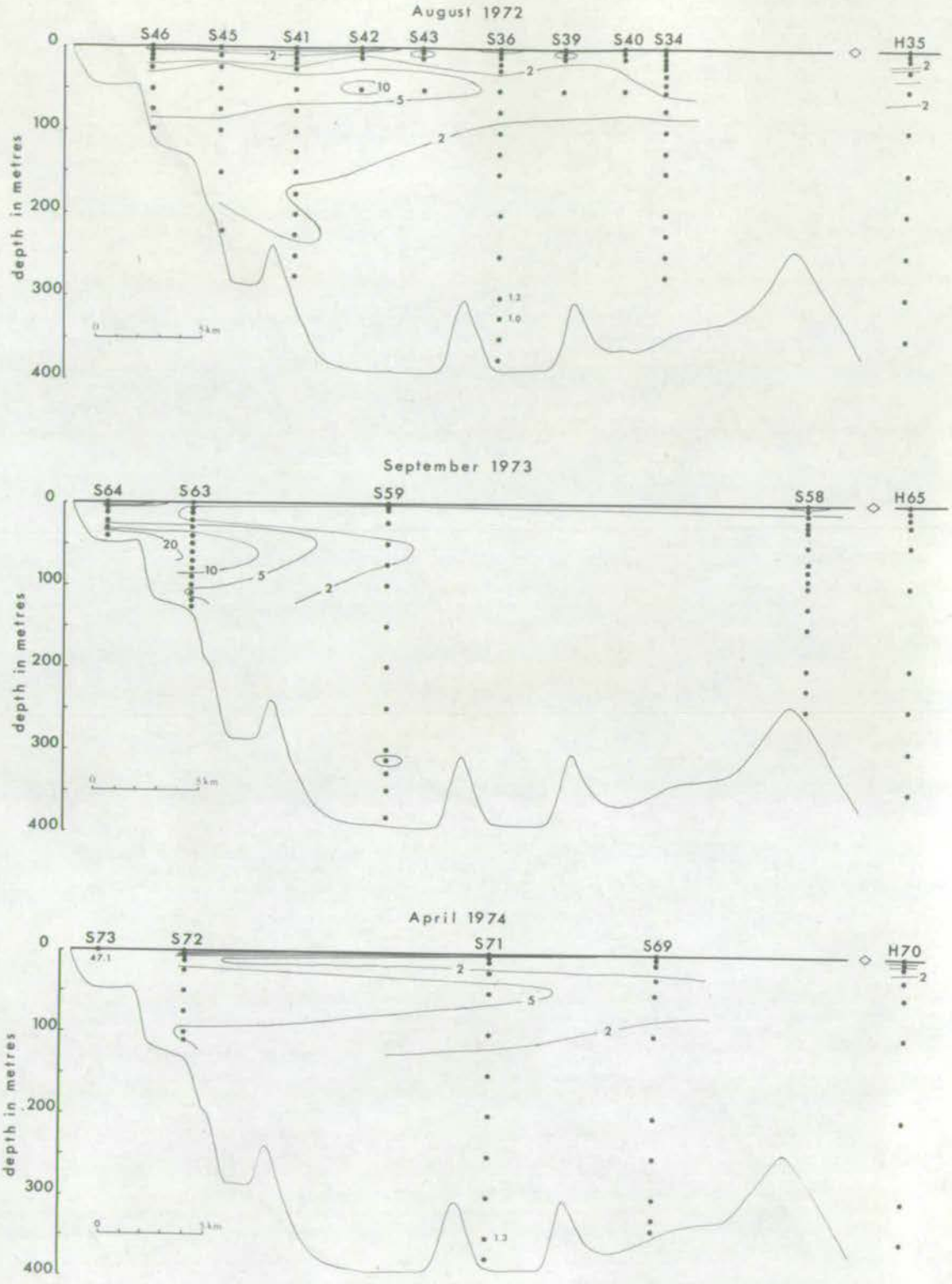


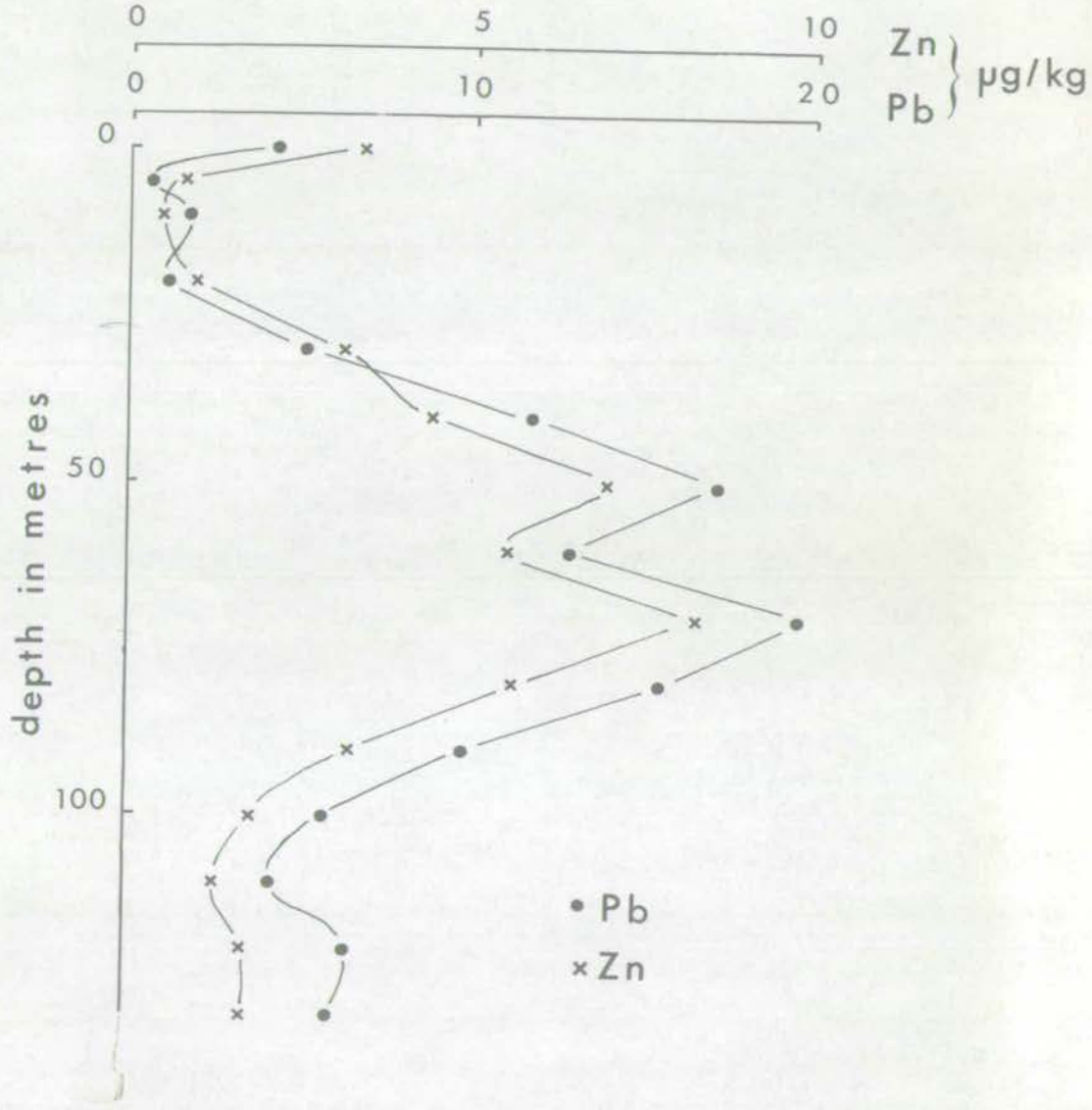
Fig. 8.1. Lateral and vertical distribution of particulate Pb during August 1972, September 1973 and April 1974 (isopleths at 2.5 (?) and 20 µg/kg).

particularly in the extreme south. Maximum concentrations of 26.9 µg/kg Pb and 13.5 µg/kg Zn were measured in the harbour basin of Odda. Here the depth profiles of Pb and Zn are similar (Fig. 8.2) and show clearly a northward dispersal of Pb and Zn in the sub-surface waters and in a thin surface outflow. The shallow autumnal inflow that has been identified by a study of the hydrography (3.7) is characterized by low metal content. This is seen to overlie an extensive outward moving undercurrent which appears to carry the bulk of heavy metal contaminants out of the fjord (Fig. 8.1). This autumnal inflow is presumably responsible for the piling up of contaminants, including that of Fe (p. 88), in the south (S 63 and S 64, Table D 5, Appendix D).

Sub-surface waters in the vicinity of the smelting works contain particulate matter displaying a mean Zn/Pb ratio of ~0.4. In the middle of the fjord (S 59) this ratio has decreased to ~0.15 in waters of 50 m to 100 m depth. Such a change provides further support for the contention that particulate Pb behaves very differently from Zn in the fjord.

In April 1974, particulate Pb and Zn were measured in samples before and after washing with distilled water (see Price and Skei, 1975, Appendix E) (p. 76). The results tabulated in Table 6.1 reveal a considerable loss of both metals upon washing. The losses of Pb from most samples are 50 to 80%; those for Zn are significantly lower (0-40%) (Fig. 8.3). The vertical change in the percentage loss of metals is most pronounced for Zn, where high losses are confined to the upper 100 m of water. This suggests that

Fig. 8.2. Vertical distribution of particulate Pb and Zn at station S 63 (September 1973).



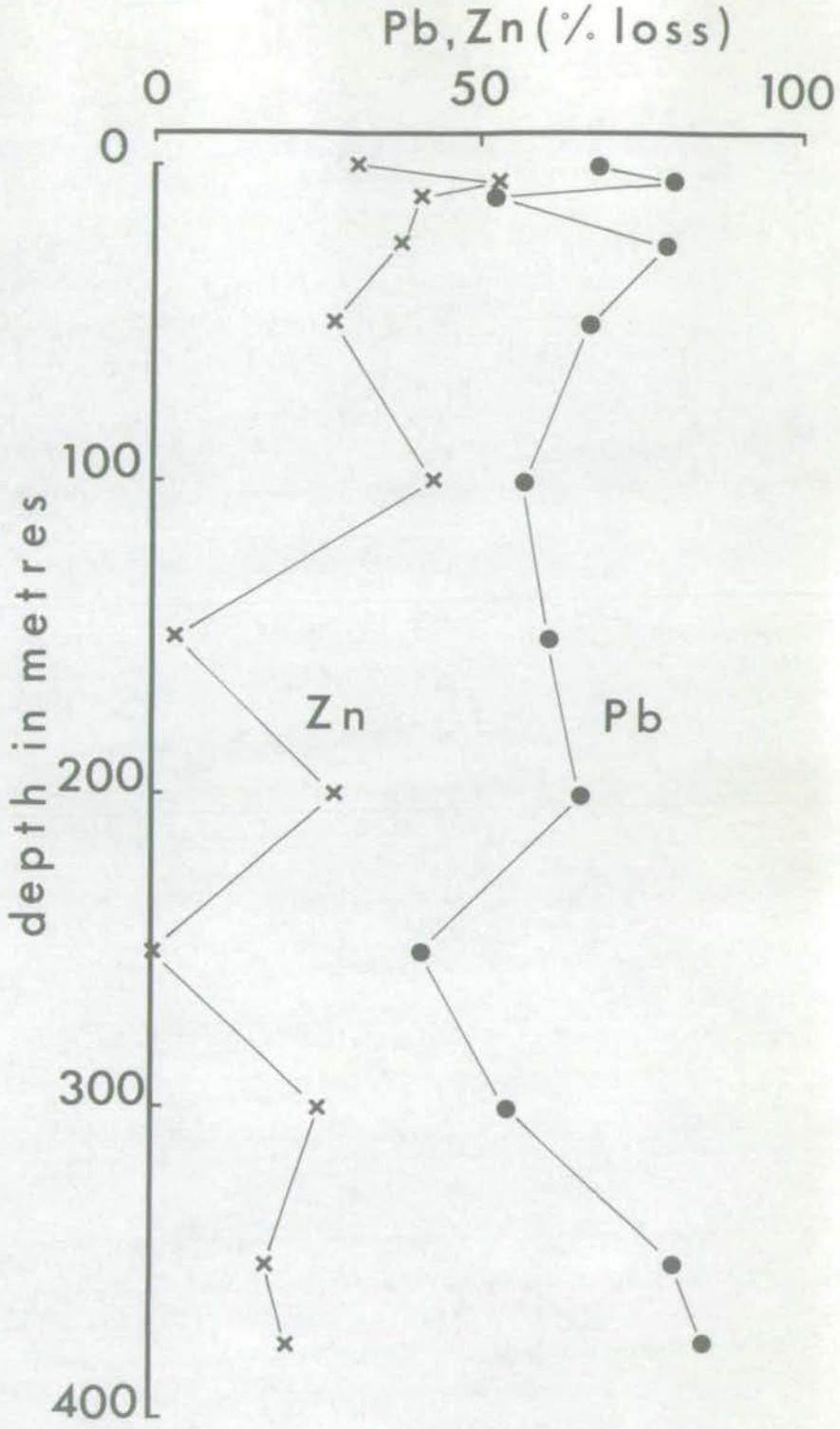
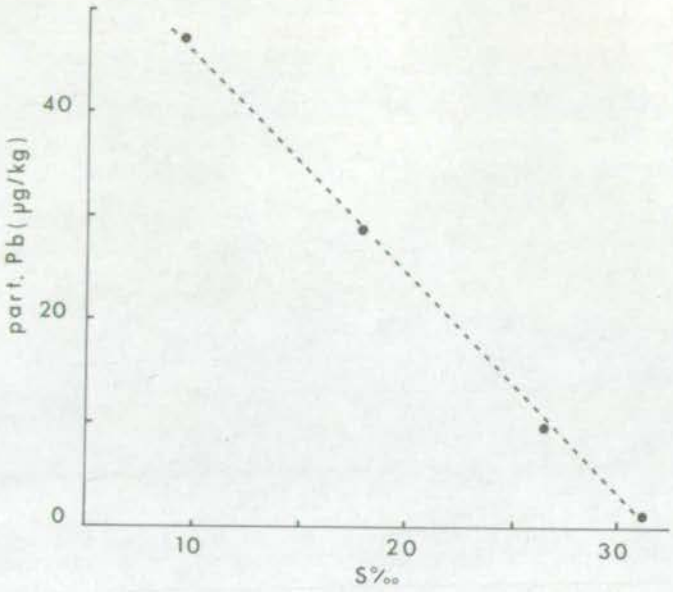


Fig. 8.3. Percentage loss of Pb and Zn from particulate matter samples (S 71) upon washing with distilled water, after drying and storage.

Zn may be largely associated with plankton (Morris, 1971). The losses of Pb are much more uniform with depth which may indicate that Pb is present in an additional phase to that holding Zn. The greatest loss of Pb (81-86%) was observed in samples collected in the deepest basin of Sörfjorden (S 71), which also display high concentrations of non-silicate Mn and Fe.

The distribution of particulate Pb (before washing) is shown in Fig. 8.1. The surface concentrations of Pb are appreciably higher in April 1974 than at other times even if the results after washing of samples are compared. The pattern implies surface (0-10 m) and intermediate (50-100 m) outflows, separated by a watermass of low particulate Pb interpreted as the compensatory inflow. This situation has been noted previously. Waters below 250 m depth are conspicuously low in their particulate Pb and Zn concentrations, that is ~1 μg/kg and 0.5 to 0.8 μg/kg respectively.

It appears that the seaward falloff in surface concentrations of Pb is mainly a consequence of dilution by mixing with seawater. This is seen from the inverse relationship between particulate Pb and salinity (Fig. 8.4). Particulate Ti (or aluminium-silicates) also showed a high degree of conservatism in the surface water at this time (Fig. 5.3). In contrast, particulate Zn shows a curve linear relationship with salinity (Fig. 8.4) suggesting that some uptake of Zn onto particulate matter takes place, particularly in the middle of the fjord (S 71). As the surface water at this station displays very high concentration of biogenous Si (Table D 6, Appendix D), this may imply that Zn is taken up by diatoms.



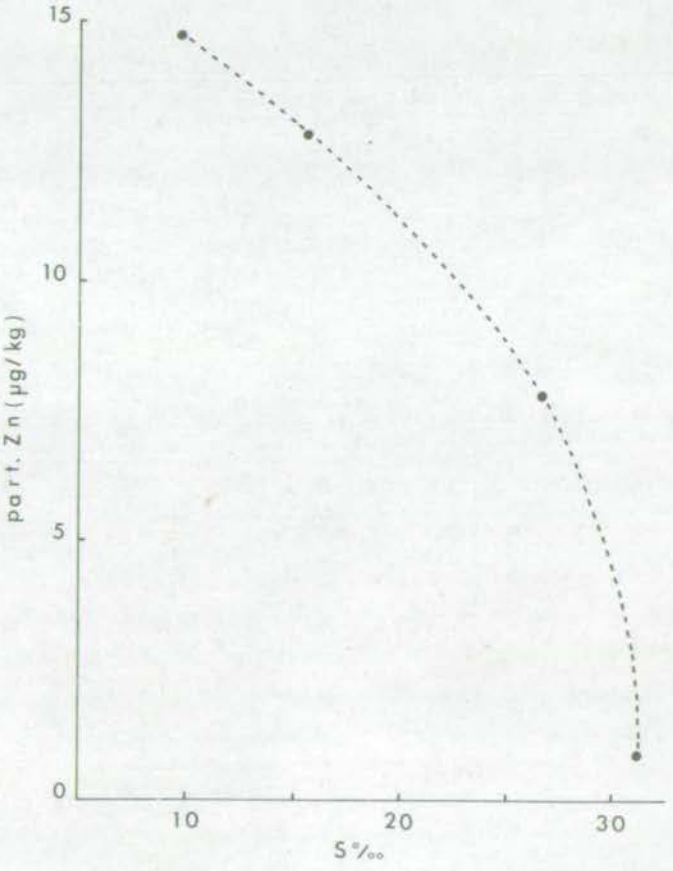


Fig. 8.4. The relationship between particulate Pb, Zn and salinity in surface waters (0 m) during April 1974.

8.3. Dissolved Cu, Pb and Zn in waters of Sörfjorden at various seasons

As the data for dissolved Cu and Pb are sparse, most attention will be paid to the distribution of dissolved Zn.

In August 1971 dissolved Zn was analysed through depth profiles at stations (S 26, 27, 28 and 31) situated in the harbour area of Odda. The results are shown in Fig. 8.5. The severity of the metal contamination in this area is most evident. Surface concentrations vary between 1060 µg/kg and 4595 µg/kg Zn. In the bottom water dissolved Zn exceeds 1100 µg/kg. The intervening waters (5-30 m) although highly contaminated, contain much lower Zn concentrations. Presumably the waters associated with these depths represent the most southerly extension of the inflowing compensating current. The surface and bottom water maxima of Zn are probably the result of direct discharge of Zn at two levels in the water (see 2.1). Some contribution of Zn to the bottom water may also be derived from dissolution of Zn from sediments containing between 1 and 10% by weight Zn (4.4). From these results and those of particulate Zn it appears that less than 1% of the total Zn in surface and bottom waters of the harbour basin resides in particulate matter. It clearly demonstrates the ability of $ZnSO_4$ (2.1) to dissolve in seawater, the low pH in these waters (p. 84) increases its solubility (O'Connor and Renn, 1964).

Samples collected in August 1972 were analysed for dissolved Cu, Pb and Zn. The levels are generally higher than can be accounted for by natural enrichment of dissolved metals in the

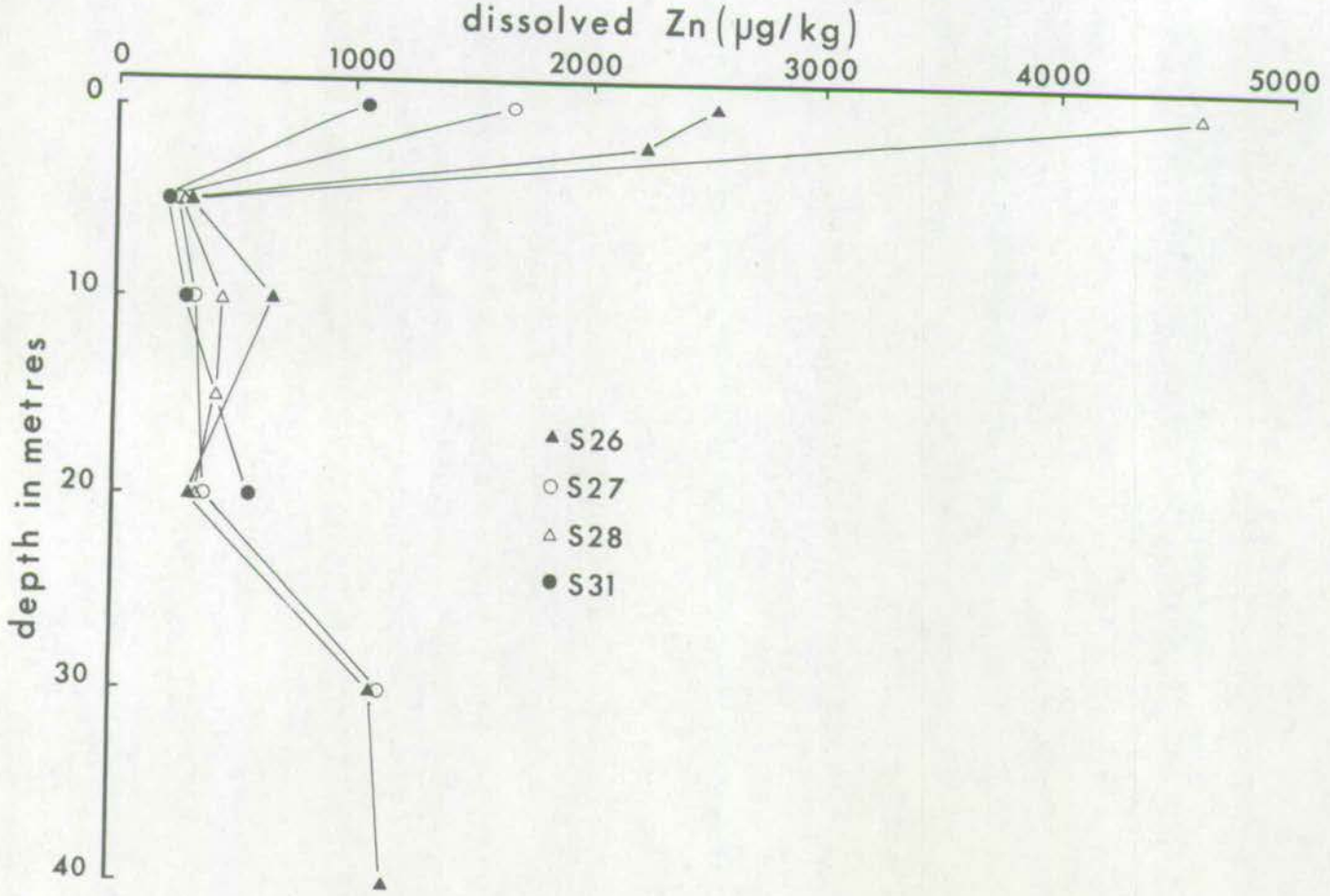


Fig. 8. 5. Vertical distribution of dissolved Zn in the harbour area of Odda during August 1971.

water during plankton blooms (i.e. Cu $\sim$4 μg/kg, Pb $\sim$4 μg/kg and Zn $\sim$20 μg/kg, Knauer and Martin, 1973). The seaward decrease of Cu concentrations is pronounced and indicates that serious Cu-contamination is effectively confined to a very small area in the south of the fjord (S 45 and S 46). The distribution of dissolved Zn (Fig. 8.6) shows fairly uniform concentrations ($<$ 200 μg/kg) in the surface water and conforms to the salinity distribution (3.2). Hence, the dilution of Zn as a surface contaminant relates to the mixing with seawater. When runoff is high (e.g. August 1972) the percentage of entrained seawater relative to the total outflow is small, due to strong density stratification. Dilution and dispersal of the contaminated volume at 25 to 100 m is more pronounced (Fig. 8.6), and a rapid seaward falloff of Zn concentrations is observed. Below the halocline the stability of the water is weak, promoting both mechanical mixing and turbulent diffusion (Pritchard, 1959). In spite of this, distinct maxima of dissolved Zn and Pb occur within the fjord at 25 m depth, coinciding with the interface between the compensating current and the midwater outflow (3.9). This interface represents a layer of no-net-motion, that is where horizontal advection is minimal. Accumulation of organic matter at such interfaces has been observed in the oceans (Bogdanov and Shaposhnikova, 1971). However, there is nothing to indicate from the results of particulate metals that this surface traps particles which could undergo metal regeneration and creating the observed maxima of dissolved Pb and Zn. An alternative and more plausible explanation for these maxima of Pb and Zn at this constant depth in

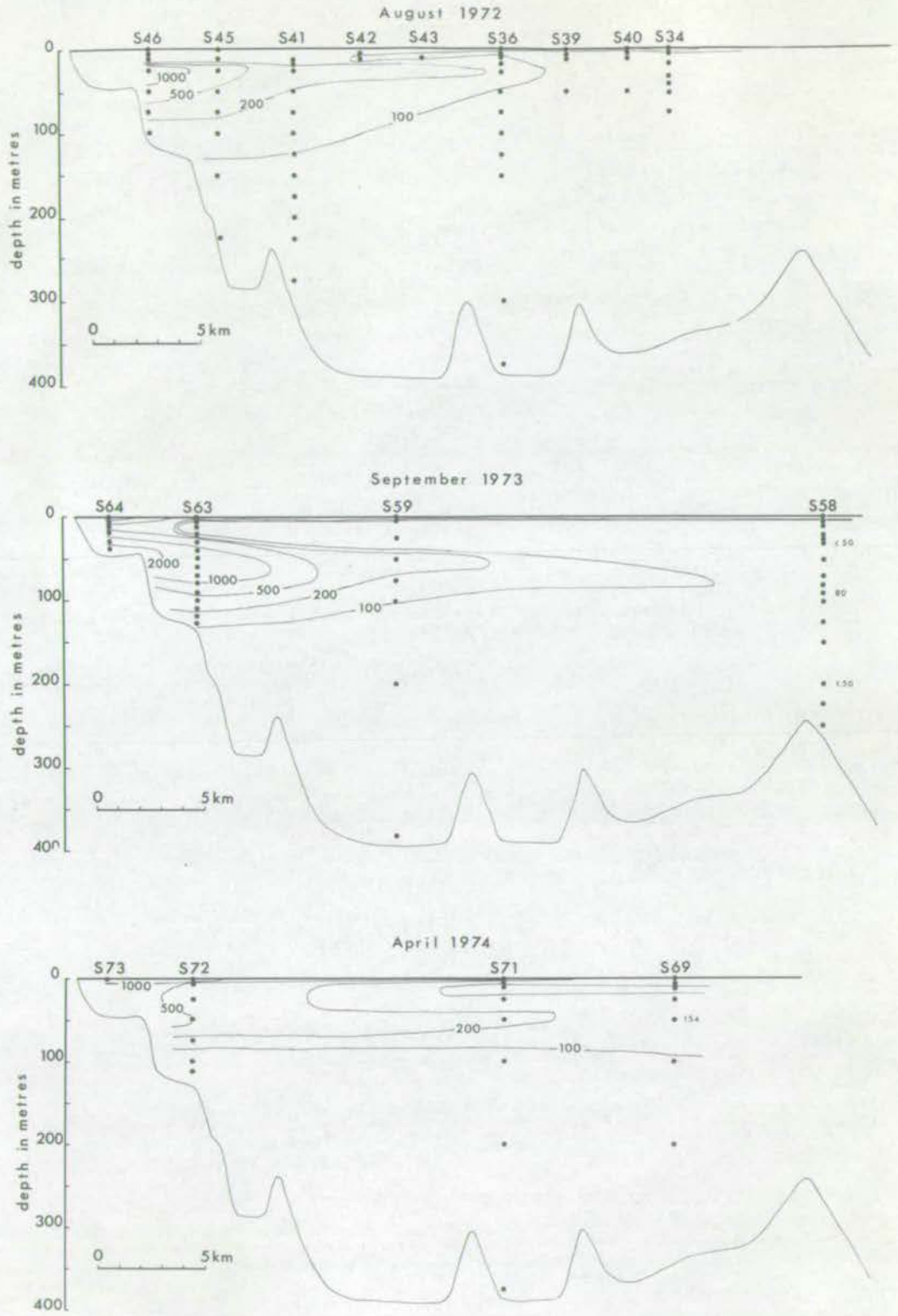


Fig. 8.6. Lateral and vertical distribution of dissolved Zn during August 1972, September 1973 and April 1974 (isopleths at 100, 200, 500, 1000 and 2000 µg/kg).

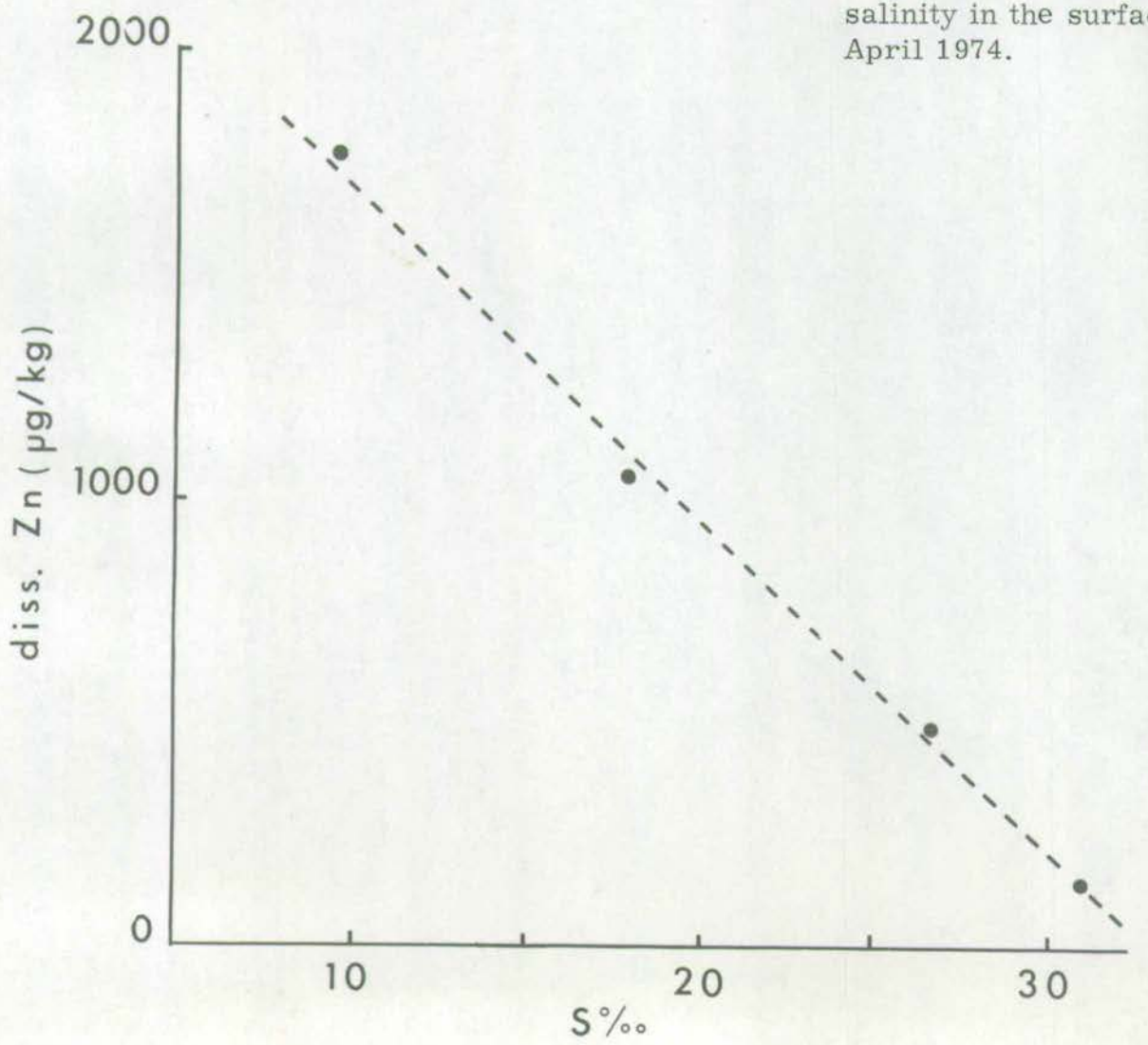
the fjord, is that the metals after being released from the source, spread horizontally along an iso-density surface. Revelle et al. (1955) have given a striking example of the difference in the scale of horizontal and vertical mixing by showing that radioactive material released at a point below the main thermocline spread over an iso-density surface and covered an area of 100 km^2, while its vertical extent did not exceed 1 m.

The analyses of particulate metals in September 1973 provide evidence of greater metal contamination than those of August 1972. This is also seen for the dissolved metals, as illustrated by Zn (Fig. 8.6). The high surface concentrations of Zn are largely associated with the small amounts of seawater entrained. However, relative to runoff and surface flow the entrainment is large, hence there is a significant northward decrease in the surface concentrations of Zn, (cf. August 1972). Fig. 8.6 also reveals that the position of the midwater outflow varies. The somewhat deeper located outflow in September compared to August 1972 is linked with autumnal shallow inflow of metal-impoverished water (3.7).

In April 1974 the overall trend in the distribution of dissolved Zn (Fig. 8.6) is similar to that described above, differing in two respects. Higher concentrations of Zn are seen in a very thin surface layer and lower concentrations can be noted in waters of intermediate depth. The rapid seaward decrease of Zn concentrations in the surface water appears to be a consequence of an extensive entrainment of seawater relative to the surface flow (see above).

As a result an inverse relationship between dissolved Zn and salinity can be established (Fig. 8.7). It should, however, be stated at this point that while dilution by seawater has been emphasized as the major factor responsible for the seaward decrease in metal concentrations, other mechanisms such as biological uptake and adsorption by detrital particulate matter may also occur (Fig. 8.4). However, these alternative mechanisms are effectively eclipsed by the very high metal contamination, and dissolved Zn appears to have conservative properties in the surface water (Fig. 8.7).

Fig. 8.7. The relationship between dissolved Zn and salinity in the surface water (0 m) during April 1974.



CHAPTER 9

PARTICULATE MATTER IN THE BOTTOM WATER OF SØRFJORDEN

An increase in turbidity in bottom waters of fjords (Jerlov, 1953; Pickard and Giovando, 1960; Folger et al., 1972) and above deep ocean slopes (Ewing et al., 1971; Jacobs et al., 1973) has been described in many studies. The high turbidity water above the seabed in fjords, termed the bottom nepheloid layer, is normally confined to the bottom 100 or 200 m (Pickard and Giovando, 1960). It is assumed to originate from bottom sediment disturbances, and is characterized by an increase in particle density with depth. Furthermore these layers in the oceans tend to contain a greater proportion of small size particles ($< 2\ \mu$) than particulate matter found in the overlaying waters (Jacobs et al., 1973), with consequently longer residence times in the water (Sachett and Arrhenius, 1962).

Published information on the composition of the particulate matter in nepheloid layers is sparse. For this reason the chemistry of the bottom nepheloid layer in Sörfjorden has been investigated and related to various parameters, especially the composition of the underlaying sediments and the particulate matter in the shallow and intermediate waters. Unfortunately as bottom waters were not collected closer than ~20 m from the seabed, the total extent and range in chemical composition of the bottom nepheloid layer at different stations and at various sampling seasons have probably not been realised.

The particulate matter in the deeper waters of Sörfjorden, especially stations S 36 (1972), S 59 (1973) and S 71 (1974) occurring over the deepest basin, have been examined for variations in the abundance and composition of its terrigenous, biogenous and authigenic constituents. Criteria delineating these constituents and their variation in composition are the same as those given in Chapters 5, 6 and 7.

Fig. 9.1 clearly shows an increase in Al and hence detrital alumino-silicates in the bottom waters, extending some 150 m to 200 m above the seabed. As concentrations generally increase toward the seabed they are consistent with a pattern developed from a process of sediment resuspension (Ewing et al., 1971). The increase is most pronounced at S 71 (April 1974). Stations S 36 and S 71, identically positioned, are separated from S 59 by the Hovland Sill. The Al profile at S 59 is complicated by a conspicuous increase of Al concentrations at 300 m depth (Fig. 9.1) which may be a consequence of erosion and resuspension of sill sediments and their inward transport.

In Table 9.1 the element/Al ratios in particulate matter of the bottom 200 m at stations S 36, S 59 and S 71 are given. It appears that the K/Al ratios of the bottom water particulate matter covary with the concentrations of total alumino-silicates present; that is, when alumino-silicates are abundant, they tend to be higher presumably due to a coarser grain-size (p. 45).

Mg/Al ratios in samples of the bottom water particulate matter also show considerable differences with respect to time of

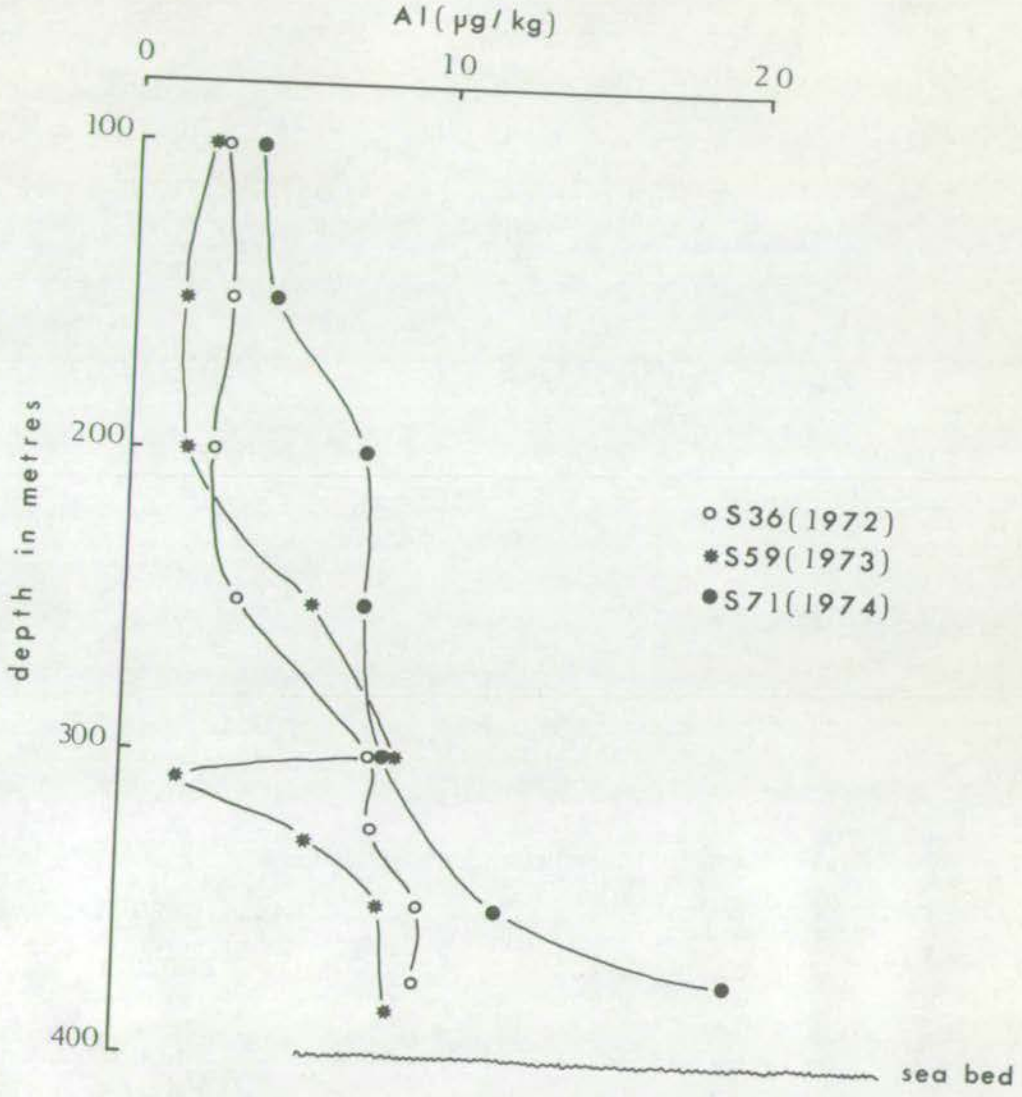


Fig. 9.1. Vertical distribution of particulate Al in the bottom 300 m of Sörfjorden during various periods of sampling.

Table 9.1. Element/Al ratios in the particulate matter of the bottom nepheloid layer of Sørfjorden

Cruise, date and station	Depth (m)	K/Al	Mg/Al	Ti/Al	Mn/Al	Fe/Al
Cruise I August 1972						
S 36	200	0.40	0.34	0.053	0.35	1.68
	250	0.39	0.41	0.040	0.33	1.41
	300	0.38	0.35	0.048	0.33	1.58
	325	0.42	0.32	0.050	0.30	1.25
	350	0.43	0.34	0.053	0.27	1.52
	375	0.41	0.34	0.049	0.30	1.29
	mean	0.41	0.35	0.049	0.31	1.46
Cruise II September 1973						
S 59	200	0.51	0.67	0.050	0.50	1.64
	250	0.39	0.58	0.039	0.70	1.44
	300	0.36	0.46	0.049	0.58	1.05
	310	0.34	0.58	0.054	0.98	1.28
	330	0.36	0.43	0.047	0.69	1.01
	350	0.39	0.46	0.040	0.69	0.96
	385	0.38	0.46	0.038	0.93	0.91
	mean	0.39	0.54	0.045	0.72	1.18
Cruise III April 1974						
S 71	200	0.42	0.37	0.047	0.26	1.56
	250	0.42	0.36	0.046	0.55	1.89
	300	0.42	0.38	0.046	0.54	1.49
	350	0.45	0.43	0.042	0.70	1.35
	375	0.43	0.41	0.041	0.61	1.25
	mean	0.43	0.36	0.044	0.53	1.51
Bottom sediments[1]		0.38	0.23	0.076	0.01	0.77

1 not salt corrected

sampling and the composition of the bottom sediment (Table 9.1). They tend to be inversely related to K/Al ratios, for example, in September 1973 (S 59) the bottom water particulate matter displayed low K/Al and high Mg/Al ratios. This implies that during periods of high turbidity near the seabed the bottom nepheloid layer contains coarser particles of a higher K/Al and a lower Mg/Al ratio than during periods of less intense sediment resuspension. The underlaying sediment shows a very low Mg/Al ratio (0.23, Table 9.1) and the true ratio is presumably even lower as no salt corrections on the sediment data were made.

The lower Ti/Al ratios in the particulate matter compared with the sediment also provide evidence of fine-grained sediment being held in the deep waters (p. 45). There is, however, no conclusive evidence of any significant change in Ti/Al ratios in the bottom particulate matter at different periods of sampling, as was seen for K/Al and Mg/Al.

The trends in alumino-silicates as described above, can be the result of either preferential resuspension of the fine-grained fraction of the sediment by bottom currents or resuspension of total sediment and selective retention of the finer grained material in the water (Sachett and Arrhenius, 1962). For any single event of sediment resuspension, preferential or otherwise, an exponential increase of alumino-silicates (Al) with depth would be expected. The nearest approach to this pattern is seen at station S 71 (Fig. 9.1). One would also expect to see a vertical gradient in the chemistry of the particulate matter (demonstrated by K/Al, Mg/Al and Ti/Al)

in the bottom 200 m of water, such as a decrease in Mg/Al ratios and an increase of Ti/Al ratios with depth; this has not been observed (Table 9.1). On the contrary, the chemical composition of particles in the bottom nepheloid layer is apparently not significantly different from that of particulate matter in intermediate waters and does not show any relation to the composition of the bottom sediments at all (p. 119).

An increase of biogenous Si in the bottom water is only observed during the period of high diatom production (April 1974). A photomicrograph of the particulate matter at 375 m depth at station S 71, shows an abundance of diatom fragments (Fig. 6.2).

The distribution of particulate authigenic constituents (non-silicate Fe and Mn) tends to follow the pattern described by Price and Skei (1975) for Hardangerfjorden. In Table 9.1 the Mn/Al ratios in the particulate matter of the bottom 200 m at various stations are shown. As Fe is abundant as a pollutant at intermediate depths in much of Sörfjorden (Chapter 7), its covariation with Mn is obscured; therefore, the discussion will be confined to Mn. The Mn/Al ratios (Table 9.1) show an appreciable increase towards the seabed at stations S 59 and S 71. During August 1972 there is no increase in Mn/Al ratios in the deep water (S 36). These results conform to the distribution of Mn/Al ratios in the bottom water of Hardangerfjorden (Price and Skei, 1975), that is low Mn/Al ratios in August 1972 and a two- to threefold increase in September 1973 and April 1974. At all times the bottom water particulates are greatly enriched in Mn compared with the bottom sediments

(enrichment factor ~35). On the basis of this trend, Price and Skei (1975) have argued, in the case of Hardangerfjorden, that the presence of much Mn relative to Al in bottom nepheloid layers is more likely to result from sediment resuspension and preferential resettling of alumino-silicates. The amount of Mn relative to Al in the water thus relates to the time elapsed between sediment resuspension and the collection of particulate matter. Evidently the Mn/Al ratio may provide useful information on the frequency of bottom sediment disturbances which again may be related to periods of bottom water flushing. In Sörfjorden it has been shown that during August 1972 highly oxygenated waters were introduced at depths between 250 m and 400 m, vertically displacing the resident bottom water (3.8). It would follow that this resident water, now displaced upwards, should exhibit particulate matter of high Mn/Al ratio. This is clearly seen in Fig. 9.2, where high Mn/Al ratios in particulate matter are observed in waters at 25 to 100 m depth. As the time period between the emplacement of the newly formed bottom water and its sampling is small (p. 35), differential resettling of Al relative to Mn is minimal and lower, more 'normal' Mn/Al ratios (0.2-0.3) result (Table 9.1). It follows from the higher Mn/Al ratios (0.5-0.9) in particulate matter of the bottom nepheloid layers at other times of sampling (1973, 1974) that flushings were not recent events and considerable differential resettling of alumino-silicates had taken place. The somewhat irregular distribution of Mn/Al ratios in the bottom 200 m seen in Table 9.1 may indicate multiple intrusions of water into the bottom of the fjord (Price and Skei, 1975, Appendix E).

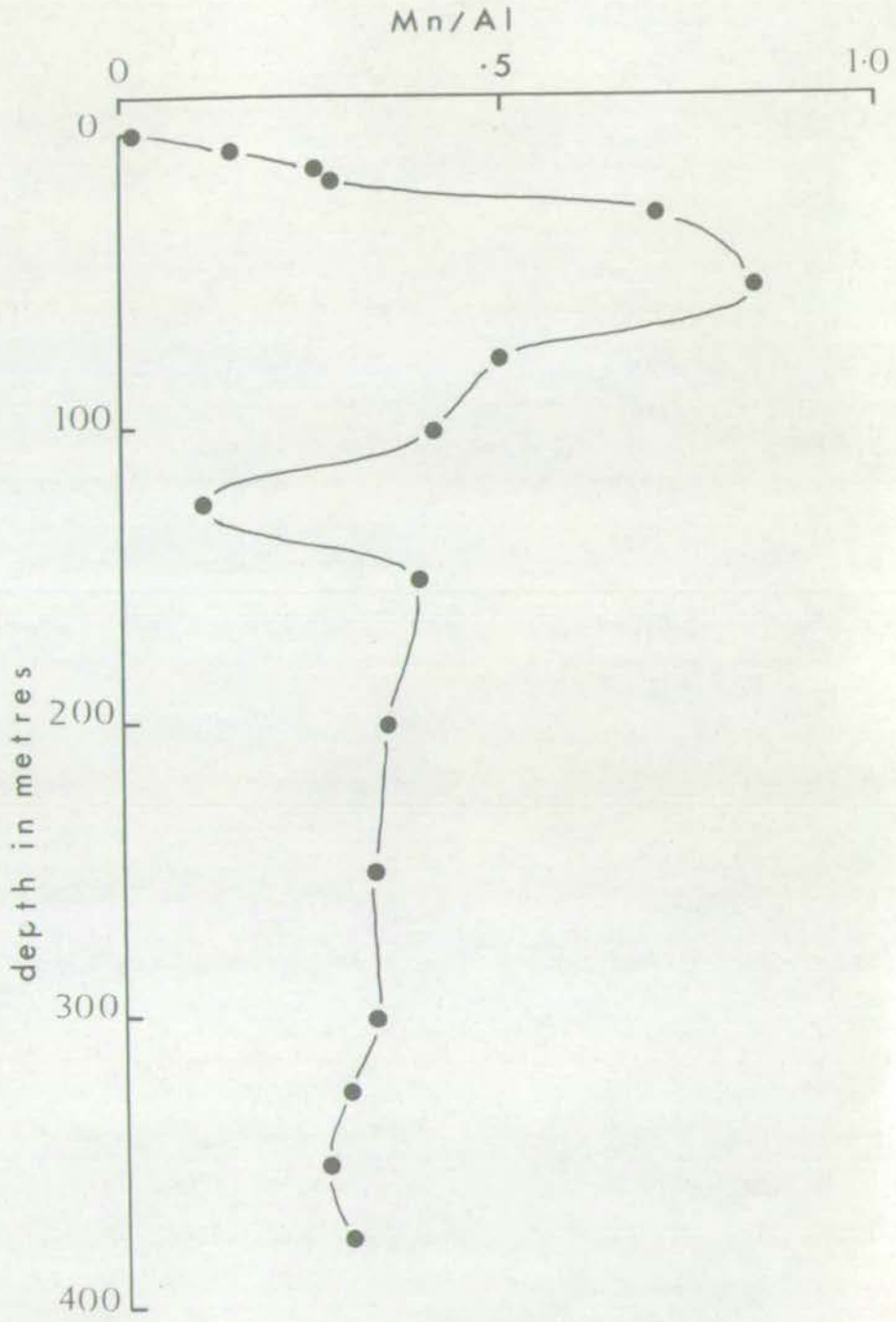


Fig. 9.2. Vertical distribution of Mn/Al ratios in particulate matter of the water profile at station S 36 (August 1972).

While the Mn/Al ratio of particulate matter in the bottom nepheloid layer may provide information on the frequency of flushing, the intensity of bottom sediment disturbance may to some extent be assessed from the concentration of particulate Al (Fig. 9.1). Apparently, the flushing which took place prior to April 1974 was much more vigorous and resuspended more material than the flushing in August 1972.

PART V

TRANSPORT AND SEDIMENTATION

CHAPTER 10

THE TRANSPORT AND SEDIMENTATION OF NATURAL AND POLLUTANT CONSTITUENTS IN SØRFJORDEN

It may be profitable to consider by using simple mass-balance calculations, the fate of both natural and pollutant constituents introduced into the fjord during the last 50 years, the period over which Sörfjorden has been subject to industrial contamination. In order to undertake such an examination many assumptions must be made, many of which are not well founded, especially with regard to the input of various materials. Even so, it is hoped its result will provide some estimate of the relative proportions of both natural and pollutant elements that are likely to be retained in the fjord. Additionally, it may provide limits of the residence time of certain constituents within the waters of the fjord. Such calculations may also serve to illustrate some of the more important problems that may have been overlooked in this and other studies in fjords and estuaries.

In order to simplify such calculations, particulate Al and dissolved Zn have been taken to represent the input of natural and pollutant elements into the fjord. The quantities of pollutant Al and particulate Zn are neglected, and 'natural' Zn is subtracted from any calculations.

10.1. The introduction of particulate Al to the fjord

Any accurate calculations on the amounts of river runoff into Sörfjorden and the amount of Al held in this water are subject to difficulty. Continuous measurements of freshwater discharge in the river Opo during 1972 (Environmental Committee Report, 1973) showed considerable variations from week to week (Fig. 1.2) and it is possible that the annual runoff of 2×10^9 m^3 for all rivers leading into Sörfjorden, as assumed here, is not a representative yearly rate for the last 50 years.

The estimate for the amount of particulate Al carried in this runoff is subject to considerably greater error. It is known that the capacity of rivers to transport sediment varies enormously with their rate of discharge (Nelson, 1970). Instead of a linear relationship, as assumed here, an exponential relationship is probably more accurate. However, in the river Opo drainage system, Lake Sandvevann (Fig. 1.5) effectively traps much of the river sediment (Aarthun, 1961) and it is possible that the ensuing outflow from the lake contains particulate matter more linearly related to the flow rate than in 'normal' rivers.

Runoff from the river Opo has been shown to vary between 0.6 m^3/sec and 389 m^3/sec, with an average annual flow of 37.4 m^3/sec (Environmental Committee Report, 1973). At the time of sampling in August 1972, runoff in the river Opo was ~ 85 m^3/sec (calculated from Fig. 1.2) and mean particulate Al was 0.5 mg/kg water. Assuming a linear proportionality between flow and carrying capacity, the annual mass of particulate Al carried into Sörfjorden

by all rivers is estimated at 740 tons, indicating an input of 3.7×10^4 tons over the last 50 years.

10.2. The introduction of pollutant Zn to the fjord

The discharge of industrial waste (Zn) has varied with time. Hence, instead of using a fixed rate of discharge we will consider the discharge in terms of limits between 6 tons Zn per day (the present (1972) discharge rate) and 3 tons per day, an assumed mean rate over the last 50 years, based on estimates of production figures and composition of waste residue (Environmental Committee Report, 1973).

10.3. The mass-balance of natural sediment

At the outset Sörfjorden will be considered to approximate a steady state system, that is, the mean level of input of particulate Al, its transport and its deposition either within Sörfjorden or outside have remained constant with time (50 years). We can now attempt to balance the total input of particulate Al (3.7×10^4 tons) with that sedimentated in the fjord.

a) Deposition of sediment.

Although no direct measurement on sediment accumulation rate has been determined, some assessment of its rate or variation in accumulation in different parts of the fjord can be made by observing the depth of penetration of pollutant metals. For convenience, the fjord has been subdivided by area and volume into seven regions (Fig. 10.1), and the mean depth the pollutant (Zn) penetrates the sediment has been calculated for each area. Except

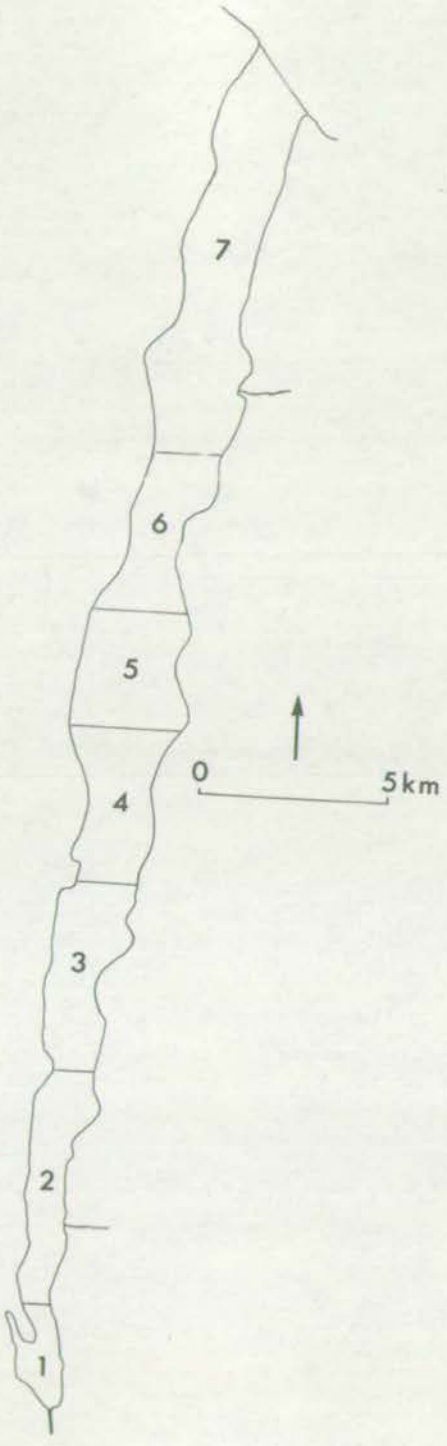


Fig. 10.1. Areal sub-division of Sörfjorden (1-7) used in connection with mass-balance calculations.

for greater accumulation of metals in the harbour area (1, Fig. 10.1), the penetration depth of pollutant Zn is rather constant in the fjord and averages ~10 cm. This suggests a mean accumulation rate of 0.2 cm/year. Such a value is in accord with an estimate for the sediment accumulation rate for Hardangerfjorden (0.5 cm/year , Holtedahl, 1965) and is within the range 0.15-0.60 cm/year for most estuaries (Rusnak, 1967).

The above calculation presupposes that the vertical extent of metal enrichment in surface sediments involves only the anthropogenic metal input, and assumes no vertical mechanical redistribution by bioturbation (Nichols, 1974) or bacterial enrichment processes (McLerran and Holmes, 1974). The same assumptions were made by Bruland et al. (1973), Capuzzo and Anderson (1973), Chow et al. (1973) and Erlenheuser et al. (1974) when considering the influence of industrialization on the metal content in sediments and its application in establishing sedimentation rates (Capuzzo and Anderson, op. cit.; Erlenheuser et al., op. cit.). The use of this method tends to be restricted to grossly polluted sediments. In normal sediments a varying degree of postdepositional migration of metals (notably Zn, Pb and Cu) occurs and leads to metal enrichment at the sediment surface (Hallberg, 1973; Price, 1973; Taylor, 1974).

For the purpose of estimating the mass of accumulated sediment in the past 50 years, the surface of deposition has been taken as the surface area of the fjord (63 km^2, Table 1.1), rather than the true surface area of the bottom of the fjord. This adjustment allows for variations in sediment accumulation across transverse

sections of the fjord. The mean sediment accumulation rate (0.2 cm/year) was computed for sediments situated only along the median line of the fjord, and must as a consequence be considered as maximum, as the rates of sediment accumulation decrease rapidly towards the sides of fjords (Doff, 1970).

Due to considerable areal and vertical variations in Al (Table 4.1) the mean Al content in the surface (0-4 cm) and sub-surface (4-10 cm) sediments has been estimated for each of the seven regions (Fig. 10.1)*. On this information and assuming the relative density of dry sediment as opposed to its constituents to be 1, a total of 3.8×10^5 tons of Al accumulated during this period of time. Comparison of this value with that determined for river input (3.7×10^4 tons) implies that rivers, as identified in this work, only supply a maximum of $\sim$10% of the sediment mass in the fjord via suspended particulate silicates.

The mean amount of suspended Al residing in the water for the various periods of sampling has been calculated for each of the seven regions (Fig. 10.1). This was assessed from a knowledge of the shape of the cross-sectional area for each of these, and consideration of the mass of Al at depths of 0-2 m, 2-20 m, 20-100 m, 100-250 m and 250-400 m. The mean result shows that $\sim$52 tons of suspended Al reside in the fjord waters. If we assume that the

---

* Sediments within regions 3, 4, 5 and 6 have not been analysed for Al; mean values of 7% Al in the surface and 7.5% in the sub-surface have been used, which commensurate with those levels found in region 7.

source of Al is river detritus, its residence time (T_{Al}) is $T_{Al} = Q/I$, where Q = total amount of Al present in the water (52 tons) and I = mean rate of input of Al from rivers (2 tons per day). The calculation indicates a residence time of 26 days; presumably the Al is lost to the sediments or is transported out of the fjord. Even if all the river-introduced Al were sedimentated in Sörfjorden there would still be a deficit of 3.4×10^5 tons of Al. Hence if the above calculations reflect the true nature of mass input there must be other mechanisms of sediment transport (10. 5) and another source or sources of sediments.

10. 4. The mass-balance of pollutant Zn

Calculations on the supply and removal of Zn have been applied in a similar way to Al. "Pollutant Zn" includes that amount of metal in excess of 50 μg/kg in the water and the content in those sediments having concentrations higher than 130 ppm (the content of Zn in alumino-silicates, p. 50).

In the former instance only that Zn residing in the uppermost 100 m of water in the respective regions (Fig. 10. 1) needs to be considered, as the amount of Zn derived from pollution is negligible in deeper waters.

As seen on p. 113, an assumed mean rate of discharge of total Zn over the past 50 years is 3 tons per day. Hence, some 5.5×10^4 tons of Zn have been released into the fjord over this period. The amount of pollutant Zn residing in the sediments,

calculated in the same way as for Al, is $\sim 1 \times 10^4$ tons*. This implies that ~18% of the Zn released by the local industry is incorporated in the sediments within Sörfjorden during the 50 years' period.

Calculations based on the mass of Zn residing in the upper 100 m of water in the fjord at various years of sampling (1972-74) show a considerable variation. However, it should be emphasized that these calculations are subject to considerable unreliability due to few Zn determinations and enormous areal and vertical concentration gradients. Even so, the assessment suggests that the amount of dissolved pollutant Zn residing in the water varies from approximately 660 tons (August 1972) to 880 tons (September 1973) to 1000 tons (April 1974). Using the present discharge rate of Zn (6 tons per day, p. 113), the respective residence times indicated are 100, 146 and 183 days.

As expected, the residence time of Zn in the water was found to be appreciably longer than for Al, as the former is present in a dissolved state while the latter resides in particulate matter and is more easily lost to the sediments. The longer residence time for Zn is also partly due to the very sluggish outward movement of water that seems to occur at intermediate depths. In contrast Al is largely transported in the rapid moving surface water of the fjord.

---

* This figure incorporates that Zn calculated in the immediate vicinity of Odda and which underlies the upper 10 cm layer (1.2×10^3 tons).

The variation in residence time for Zn between different periods of sampling is in agreement with the concept that the circulation in the fjord is largely governed by the runoff (p. 31). At high river discharge the water exchange increases and pollutants are flushed more efficiently out of the fjord system (see also 6.2).

10.5. Sedimentation in fjords

The various mechanisms leading to sediment accumulation in fjords have been discussed by several workers (Pantin, 1964; Holtedahl, 1965; Folger et al., 1972; Hoskin and Burell, 1972). There seems to be a general agreement that settling of particles from a sediment laden, freshwater surface "plume" is the most important contributor to the accumulation of terrestially derived sediments in fjords. This mechanism is thought to be especially important in fjords receiving large amounts of glacial clays, where the concentration of suspended matter in the surface water is sufficiently high to facilitate flocculation (Hoskin and Burell, 1972; Meade, 1972). However, the surface waters in Sörfjorden contain relatively small amounts of suspended matter (<4 mg/l), possibly as a result of the trapping of sediments by Lake Sandvevann (p. 7). Calculations on the mass-balance of sediments (10.3), suggest that the amount of Al sedimentated over the last 50 years is an order of magnitude higher than that provided by rivers. Either the assessment of mean river input of Al is grossly underestimated or there is another source of Al which is far more important than river detritus. As a third alternative the estimated mean rate of sedimentation (0.2 cm/year) may be too high. The fine grain-size of the sediment in the upper

part of gravity cores does not provide real evidence of sediment slumping or transport via turbidity flows. Gravel, coarse sand, wood, etc. below 15 to 20 cm depth (4.1) were probably introduced in this manner. Although this mechanism appears sporadic, it may have a significant effect on the overall sediment accumulation rate. Holtedahl (1965) has found from textural evidence in the sediments of Hardangerfjorden that turbidity flows are frequent, and believes that they are responsible for at least 50% of the total sedimentation there. However the most plausible explanation of the discrepancy between input and sedimentated material in Sörfjorden during the last 50 years (p. 111), is an underestimation of the amounts of sediments carried by rivers. It is known that during periods of exceptional rainfall and storms, river's transport capacity increases tremendously with respect to both material in suspension and bed load (Meade, 1972). Hence, it is possible that most of the sedimentation in Sörfjorden takes place during short periods of exceptional river flow. This would explain the presence of silt and sand in the sediments. Furthermore, it would explain the abundance of quartz in the sediment (4.2) and the lack of it in particulate matter of the rivers and the fjord (5.2). It would appear that the composition of suspended particulate matter observed during the various periods of sampling is entirely different from that of material transported by rivers and fjord waters during exceptional freshwater discharge. For the same reason the chemical composition of the bottom sediments differs from that of the particulate matter in the water sampled during periods of "normal sedimentation".

While the mean rate of sediment accumulation in Sörfjorden has been estimated as 0.2 cm/year, inevitably this will vary within the fjord. In 4.3c it was suggested that the content of Mn in surface sediments is inversely related to sedimentation rate and hence Mn would provide evidence for areal change in sedimentation in the fjord. The distribution of Mn in the surface sediment along a medial profile (Fig. 4.8) indicates that the lowest present sedimentation rate occurs in the middle of the fjord and increases towards its head and mouth. The southward increase in sedimentation may be explained partly by the main river discharge entering the fjord from the extreme south, and to some extent by a greater accumulation of industrial effluent towards the head of the fjord. The increase to the north is consistent with either a local introduction of sediment from the river Ullensvang (Fig. 1.1), the third largest river in the area, or a redistribution of the fine-grained sediments constituting much of the outer sill of the fjord (Hausaneset Sill, Fig. 1.3). Analyses of suspended particulate matter outside the entrance of Sörfjorden do not indicate that any substantial amount of sediment is brought in from outside the fjord.

10.6. The fate of pollutants in fjords

Evaluation of the effects of waste discharge upon estuarine systems is one of the most complex technical problems confronting those concerned with the resolution of water pollution problems. The prediction of mixing, dilution and movement of pollutants in the watermasses is complicated due to the liability of pollutants to undergo physio-chemical changes in the water.

Such mechanisms are dissolution, precipitation , adsorption onto organic and inorganic phases, uptake into organisms, sedimentation and possible remobilisation and recycling.

Pollutants discharged into a fjord may be diluted by water from two sources, 1) a freshwater source, and 2) inflowing seawater. Most studies of the dispersion of pollutants in estuaries consider cases where the effluent is discharged into the river, and its fate in the fjord is predicted from the salinity distribution. Secondly, the inflow of seawater into estuaries is often considered to be truly of a tidal character, carrying pollutants back and forward.

The situation in Sörfjorden is, however, more complicated. First the pollutants are not introduced into freshwater but are mixed with seawater before being released at different levels (0-20 m) into the fjord. Second, while a multi-layered flow system has been recognized, the velocities of water flow are unknown. It is doubtful that these can be measured with any confidence, at least in the intermediate water. For instance, if the residence time of Zn in the fjord is 150 days, the mean outward flow velocity is only ~0.3 cm/sec.

The fate of a pollutant in the fjord has been examplified using Zn and considering the fjord as a steady-state system over a period of 50 years. It is interesting to consider the mechanisms by which the 18% of the Zn released from the industry enters the sediments. That dissolved Zn in the surface waters is not efficiently removed is testified by its apparently conservative behaviour with respect to salinity, (Fig. 8.7). Below the halocline

where most of the Zn occurs (Fig. 8.6) the concentration of particulate alumino-silicates is very small. Hence, sorption of Zn onto clays (Krauskopf, 1956) and subsequent sedimentation removes only a very small amount of Zn from the water. Removal of Zn by plankton (p. 98) and its fallout in seston may account for some of the Zn incorporated into sediments. However, owing to the mobile nature of Zn (cf. phosphorus) upon breakdown of the organic matter (Price and Skei, 1975, Appendix E), the amount removed in this way is also likely to be small. The extensive accumulation of Zn in the sediments of the extreme south is presumably the result of direct fallout of introduced particulate Zn (e.g. $ZnO.Fe_2O_3$, Table 2.3 and 4.2). Most of the dissolved Zn appears to escape into Hardangerfjorden.

The fate of other metal pollutants in Sörfjorden (e.g. Cu and Pb) has not been quantitatively assessed, but it appears to be different from Zn. Both Cu and Pb concentrations show a rapid northward decline in the water; suggesting that in contrast to Zn they are quickly incorporated into the sediments (Fig. 4.8). This is most likely due to direct fallout of introduced, almost insoluble Cu and slightly soluble Pb compounds (2.1). Some particulate Pb appears to escape into Hardangerfjorden at intermediate depths, while most of the Cu seems to be retained within Sörfjorden.

Analyses of plankton (mainly dinoflagellates) collected in Sörfjorden showed ranges of 17 to 31 ppm Cu, 44 to 110 ppm Pb and 488 to 652 ppm Zn (dry weight). These are consistently higher

than ranges found in phytoplankton from coastal waters, particularly for Pb and Zn (Cu = 3-15 ppm, Pb = 7-9 ppm and Zn = 19-122 ppm dry weight, Martin and Knauer, 1973).

Unusually high concentrations of these metals have also been found in mussels in Sörfjorden (Havre et al., 1973) and in brown algae (Haug et al., 1974; Stenner and Nichless, 1974). An interesting point is that biological investigations in the most seaward parts of Hardangerfjorden give evidence of pronounced Zn pollution, while Cu and Pb reach normal levels some 35 km from Odda (Haug et al., 1974). This supports the results of the mass-balance calculations of Zn (p. 117), showing that some 80% of the total pollutant Zn released escapes into Hardangerfjorden.

PART VI

SUMMARY AND CONCLUSION

An integrated study of the hydrography and the chemistry of water and sediments of Sörfjorden, a polluted fjord on the west coast of Norway, was performed to obtain a better understanding of the physio-chemical processes which occur in fjords at different states of runoff. To this end the chemistry of suspended particulate matter and dissolved metals have been used together with hydrography and hydrochemistry to identify and trace the movement of certain defined water bodies in the fjord. This approach is likely to assist our understanding of problems involved in the disposal of industrial wastes in this and other fjords.

The hydrography reveals an upper layer estuarine circulation at all runoff situations, comprising a seaward surface flow (10-20 m deep at high runoff and less than 10 m at low) and a compensatory underflow ($\prec$ 30 m deep) to replace entrained seawater. The salinity in the surface flow shows little change from head to mouth of the fjord at high runoff, which implies that entrainment relative to river discharge is small. The upward transport of seawater is to some extent obstructed by a strong halocline. During low runoff surface salinities show, in contrast, a pronounced seaward increase due to high relative entrainment, although net entrainment is assumed to be much less.

The hydrochemistry (dissolved O_2, PO_4-P and SiO_4-Si) has provided information both on the biochemical processes in the water and on the renewal of the deep waters ($>$ 100 m). Dissolved

oxygen is high (> 5 ml/l) in the upper 50 m as a result of the combined effect of turbulent mixing with atmospheric oxygen and photosynthesis in the euphotic layer. The pronounced decrease of oxygen in the underlaying waters (100-200 m) is related to biochemical breakdown of organic matter (Reid, 1965). Oxygen in the basin water (>250 m) is controlled by advective watermasses, implying that renewing of bottom water, identified by an increase of oxygen, was a recent event in August 1972 but not during other periods of sampling.

The biological demand on nutrients leads to a depletion of phosphate and silicate in the euphotic layer (0-25 m). However, the behaviour of phosphate as a nutrient is obscured by the strong influence of phosphate contamination from a H_3PO_4-plant at the head of the fjord. The distribution of this phosphate contamination suggests a pronounced outflowing waterbody at intermediate depths (25-150 m). In waters unaffected by contamination (Hardangerfjorden), the vertical distributions of phosphate and silicate demonstrate quite different behaviours with respect to regeneration processes (Grill and Richards, 1964). Phosphate shows little change below 100 m depth in contrast to silicate which tends to increase with depth. This either reflects differences in the rate of dissolution from sinking biogenous matter, or indicates some dissolution of biogenous silica in bottom sediments. It follows that the levels of the dissolved silicate in the bottom water are related to the residence time of the water. Its concentrations there, and its secular variation, are largely controlled by the flushing. In August 1972 the concentrations of dissolved silicate in the bottom waters of Sörfjorden were similar

to those at comparable depths in Hardangerfjorden; at other times of sampling they were much higher. These observations, and those of dissolved oxygen, support the contention of flushing in or immediately preceding August 1972.

The sediments of Sörfjorden comprise sandy silts of low organic content and a uniform texture, particularly in the upper 10 cm of the sediment. At greater depths distinct layers of coarser material occur. The geochemistry of the major elements representing alumino-silicates (i.e. Si, Al, Ti, Mg and K) resembles that of other fjord sediments and shows strong relationships between these elements. Fe, Ca, P and total-C show unusual surface enrichments in sediments confined to the southern extremity of the fjord, attributed to a local accumulation of industrial waste. A pronounced enrichment is displayed by several trace metals (e.g. Cu, Pb and Zn) in these sediments, although their presence as pollutant elements pervades the entire fjord. The thickness of sediment containing these pollutant metals suggests a mean sediment accumulation rate of ~0.2 cm/year for the last 50 years. However, the variation of Mn in the surface sediments implies some areal variation in sediment accumulation rates. It is reasoned that as the rate of MnO_2 precipitation at the seawater-sediment interface is likely to be constant, a low rate of sediment accumulation (terrigenous and biogenous) will result in high Mn enrichment and vice versa. The concentrations of Mn in the surface sediments decrease towards the head and the mouth of the fjord, and display highest values in the deep basins in its middle part. Such a feature suggests local dumpings of sediment from rivers in the

southern (rivers Opo and Tysso) and in the northern (river Ullensvang) parts of the fjord.

Studies of the chemical composition of suspended particulate matter have been used to investigate:

a) the transport of sediments in fjords,

b) the partitioning of elements between various constituents,

c) the breakdown of biogenous matter,

d) the dispersal of pollutants, and

e) the problems concerned with bottom nepheloid layers.

The suspended particulate matter consists of detrital alumino-silicates, authigenic components, skeletal remains and organic matter. The amount of organic matter appears to constitute 40 to 90% of total suspended matter. Terrigenous alumino-silicates, as denoted by Al, K, Mg and Ti, are abundant at the surface of the fjord (0 m) and show a marked seaward decrease in concentrations. There is a strong interelement relationship between these elements in the particulate matter at all depths and seasons. While high K/Al and Ti/Al seem to indicate coarser grained particles, high Mg/Al ratios appear to typify samples of higher clay content. Plots of Ti against salinity exhibit a non-conservative property of alumino-silicates during periods of high runoff. Presumably at such times river borne detritus is coarser, permitting a greater settling across the halocline. At intermediate depths the quantities of detrital silicates are small, unlike the bottom 200 m where increases are observed.

Particulate biogenous constituents, that is skeletal matter

(Si, Ca) and organic matter (P, S), are difficult to classify due to the partitioning of their elements between other components (e.g. alumino-silicates, pollutants and authigenic phases). Despite this their distributions portray certain patterns of behaviour. Biogenous Si shows characteristic seasonal changes, being abundant during the spring diatom blooms (i.e. April 1974). It displays its maximum concentration within the euphotic layer; below there is a general falloff in concentration. The amounts of biogenous Si at depth appear to relate to surface productivity. In contrast, organic matter, as represented by P and S, also covaries with variations in productivity but shows a rapid breakdown in the upper 200 m of water; below there are no seasonal changes in the abundance of particulate P and S. This difference in behaviour of particulate, biogenous Si and P between surface and deeper waters conforms to that of dissolved silicate and phosphate.

While Si dominates as a biogenous constituent in diatoms (mainly Skeletonema costatum) during April 1974, Ca appears in large quantities during September 1973 as a result of a near-surface inflow of coastal water carrying an abundance of Coccolithus huxleyi (Braarud et al., 1974).

High concentrations of particulate Ca and P in the southernmost part of Sörfjorden have been attributed to discharge from industry. A large quantity of gypsum effluent, which is soluble in seawater, seems to enrich the Ca^{2+} concentration such that precipitation of $CaCO_3$ occurs in an area confined to the harbour basin of Odda, especially during periods of sluggish water circulation

(low runoff). Covariation of P and non-silicate Fe in some contaminated waters in the south, suggests formation of ferriphosphates.

The introduction of dissolved Mn and Fe into the fjord from rivers may cause precipitation, at least of 'colloidal' Fe, partly due to a freshwater-seawater interaction (Coonley et al., 1971). A conspicuous increase of particulate Mn at the halocline in the southernmost part of the fjord, where the halocline separates surface water of extremely low pH (3.7-5.6) and normal pH waters implies precipitation of Mn phases, or adsorption of Mn onto particulate matter. High particulate Mn in near surface waters where there is an abundance of biogenous matter, indicates that some Mn may also reside in organisms.

The distribution of particulate non-silicate Fe is evidently much influenced by discharge of finely dispersed (1-20μ) Fe from a zinc plant. Except for higher levels of Fe at the surface caused by river input, the distribution of Fe at intermediate depths reflects the dispersal pattern of Fe-effluent. Due to its high density ($\sim$1.09 g/ml) relative to seawater ($\sim$1.02 g/ml), it spreads down-current like a plume (Pritchard, 1959), initially following the seabed until mixing with seawater reduces its density sufficiently to prevent further sinking. This feature is observed during all periods of sampling.

Although some 60% and 100% of total Zn and Pb in industrial waste are associated with the Fe-effluent when it is released, Zn distributions in particular show little relation to the Fe-plume in the fjord waters. As these metals occur in water soluble compounds

in the waste (especially Zn) their dispersal in the fjord serves as a tracer of flow patterns of water. Dissolved Zn clearly shows outflows of contaminated water at two levels: 1) at the surface, and 2) at intermediate depths (25-150 m). The same trend is exhibited by other industrial pollutants (e.g. Pb, Cu and PO_4-P). From this a four-layer flow system has been identified in Sörfjorden, constituting an upper two-layer estuarine flow (p. 29), a midwater outflow and occasional deep water inflows. The relative position and vertical extent of the various watermasses show periodical changes which appear to be related to river runoff and transitory inflows of coastal water. Deep-water flushing often causes resuspension of bottom sediments and vertical displacement of resident bottom water.

The chemistry of bottom nepheloid layers and their relationship to the composition of the underlaying sediments have been investigated. Bottom waters in Sörfjorden show an increase of particulate Al (or alumino-silicates) during all periods of sampling, although the concentrations are variable. The composition of alumino-silicates, as illustrated by element/Al ratios, does not seem to be significantly different from that of detrital silicates of surface or intermediate waters. Furthermore, their compositions appear unrelated to that of the bottom sediments. This implies that bottom currents either resuspend a certain fraction of the bottom sediment or that the total sediment is suspended but a selective retention of the finer grained material in the water ensues.

The occurrence of much non-silicate Mn and very high Mn/Al ratios in the bottom nepheloid layer is thought to be related

to the latter. Mn/Al ratios vary significantly with respect to the time of sampling. In August 1972 they are much lower than at other times, implying total resuspension of bottom sediment caused by a contemporary flushing and little preferential resettlement of alumino-silicates. At other times the high Mn/Al ratios indicate that flushing was not a recent phenomenon and support the observations of dissolved silicate and oxygen. During bottom water flushing the resident bottom water is vertically displaced and can be recognized by its high particulate Mn content with respect to Al at intermediate depths. While Mn/Al ratios in particulate matter of bottom nepheloid layers may provide evidence of the frequency of flushing, the intensity of bottom sediment disturbance may be assessed from the concentrations of particulate Al.

An attempt has been made to quantify the amounts of sediments (using particulate Al) and pollutants (using Zn) accumulated in the fjord during the past 50 years, assuming a mean sediment accumulation rate of 0.2 cm/year. These quantities were related to estimated input via rivers (Al) and via industrial discharge (Zn). Such calculations suggest that if all particulate Al provided by rivers was sedimentated within Sörfjorden, it can only account for 10% by weight of the total sediment accumulated during this period. This discrepancy presumably reflects a gross underestimation of the rivers' transport capacity during periods of floods.

The calculations on the mass-balance of pollutant Zn suggest that some 18% of the total amount of Zn discharged during the 50 years' period reside in the sediments of Sörfjorden. The

remaining ~80% escapes into Hardangerfjorden and is probably transported as dissolved Zn in the surface and intermediate waters.

An attempt to calculate the residence time of particulate Al and dissolved Zn in the water was also made. The mean residence times were 26 days and 100-180 days respectively. That of Zn seems to be related to runoff and is smaller during high river discharge (100 days) and longest at minimum runoff (183 days). This supports earlier arguments that river flow promotes the upper water circulation.

APPENDIX A

Shipboard measurements, sample collection and preparation

i) Salinity and temperature determinations

Salinity and temperature were measured in situ with a N. I. O. portable Salinity-Temperature Bridge (Type M. C. 5). Due to the limited length of cable, readings were only possible to a maximum depth of 95 m.

Salinity and temperature readings were calibrated daily at sea against Standard Copenhagen Seawater ($S‰$ = 35.00) and a laboratory Hg thermometer respectively. Prior to each set of measurements, the electrodes were cleaned with mild detergents. The estimated precision* and accuracy for temperature and salinity are $\pm 0.2^{\circ}C$ and $\pm 0.6^{\circ}C$, and $\pm 0.1‰$ and $\pm 0.5‰$ respectively.

ii) Water sampling

Four N. I. O. polyvinyl chloride/nylon water bottles were used to sample water. Immediately on retrieval of a bottle a number of subsamples were collected. For this purpose a plastic tubing extension was fitted over the bottom tap of the bottle. Subsampling was as follows:

a) an 'oxygen bottle' (~300 ml) was filled until overflowing and care was taken to avoid inclusion of airbubbles.

---

* Precision is expressed consequently as the coefficient of variation (v_x)

$$v_x = \frac{\sigma_x}{\bar{x}} \cdot 100\%$$

where σ_x = standard deviation and $\bar{x}$ = sample mean.

The sample was immediately pickled with 3 ml $MnCl_2$ solution and 3 ml NaOH/NaI solution after which the bottle was stoppered. Analyses were commenced within 5 hours of sampling.

b) a subsample for nutrient analysis (dissolved phosphate and silicate; see p. 140) was collected in a 250 ml reagent bottle. Analyses were commenced within 5 hours of sampling.

c) during cruise B (August 1971) a glass vessel especially adapted for pH and Eh analyses was filled and the analyses were completed within 20 minutes of sample recovery.

d) during cruise I (August 1972) a 250 ml reagent bottle was filled for the determination of titration alkalinity at shore laboratory.

e) the remainder of each sample was collected in an acid-washed 4 l polyethylene jerrycan following a single rinse of the water sample. Filtration of these water samples were commenced within 8 hours of sampling.

iii) Coring

A 1.5 m stainless steel gravity corer with plastic core liner (6 cm diameter) was used to sample sediments. Immediately on retrieval of the coring device, the transparent plastic liner was removed and the core length and general lithology of the sediment were noted. The plastic liner was sealed at both ends with plastic caps and most of the water overlaying the sediment was drained off by boring a hole through the liner about 4 cm above the sediment

surface. The core was then frozen upright in dry ice and transported to Edinburgh.

iv) Plankton sampling

Plankton was sampled by near surface, oblique hauls of a nylon phytoplankton net. A small proportion of the plankton was preserved in formalin for species identification. The remaining part was immediately frozen for chemical analyses in Edinburgh.

Station logs for all cruises are provided in Table A 1 and A 2.

Table A 1

Station Logs (1971)

Cruise	Station	Date	Depth (m)	H	O	pH	Eh	S	P	C
A	S 2	21/4/71	25							+
	S 6	"	45							+
	S 7	"	50							+
	S 8	"	45							+
	S 10	"	48							+
	S 11	"	44							+
	S 12	"	7							+
	S 14	22/4/71	50							+
	S 15	"	18							+
	S 16	"	57							+
	S 17	"	55							+
	S 19	23/4/71	120							+
	S 20	"	75							+
	S 21	"	180							+
	S 22	"	280							+
	S 23	"	270							+
B	S 24	22/8/71	340							+
	S 25	"	340						+	+
	S 26	23/8/71	50	(+)*	+	+	+	+		
	S 27	"	35	(+)	+	+	+	+		
	S 28	"	25	(+)	+	+	+	+		
	S 29	24/8/71	120	(+)	+	+	+	+		
	S 30	"	280	(+)	+	+	+	+	+	
	S 31	"	56	(+)	+	+	+	+		+
	S 32	25/8/71	385	(+)	+	+	+	+		
	S 33	"	350	(+)	+	+	+	+		

H hydrography (salinity/temperature) * not reliable.

O dissolved oxygen

S suspended particulate matter

P plankton

C coring.

Table A 2

Station Logs (1972-74)

Cruise	Station	Date	Depth (m)	H	O	N	A	S	P	C
I	S 46	11/8/72	110	+	+	+	+	+		
	S 45	"	240			+	+	+		
	S 56	1/9/72	264							+
	S 41	9/8/72	300	+	+	+		+	+	+
	S 51	1/9/72	355							+
	S 42	9/8/72	395	+	+			+	+	+
	S 52	30/8/72	395							+
	S 43	10/8/72	395	+	+			+	+	+
	S 36	"	385			+		+	+	+
	S 39	9/8/72	315					+	+	+
	S 40	"	360					+	+	+
	S 34	8/8/72	300		+	+		+		
	H 35	"	730	+	+	+	+	+		
	H 47	29/8/72	110						+	+
	H 48	"	560						+	+
	H 49	"	220							+
	H 50	"	720						+	
	H 54	28/8/72	860						+	
	H 55	"	650						+	
River/lake samples										
1 Lake Sandvevann		10/8/72						+		
2 River Opo (upper)		"						+		
3 River Opo (lower)		"						+		
4 Lake Ringdalsvann		"						+		
5 River Fossa		"						+		
6 River Espe		"						+		
7 River Ullensvang		"						+		
II	S 64	28/9/73	50	+	+	+		+		
	S 63	"	120	+	+	+		+		
	S 62	27/9/73	290	+					+	
	S 59	26/9/73	395	+	+	+		+	+	
	S 74	"	390						+	
	S 61	27/9/73	390	+						
	S 75	29/9/73	310						+	
	S 58	25/9/73	270	+	+			+		
	S 60	27/9/73	350	+					+	
	H 65	30/9/73	740	+	+	+		+		
	H 66	2/10/73	540	+	+	+		+		

Table A 2 continued

Cruise	Station	Date	Depth (m)	H	O	N	A	S	P	C
III	S 73	4/4/74	50	+				+		
	S 72	"	120	+	+	+		+		
	S 71	"	390	+	+	+		+		
	S 69	2/4/74	350	+	+	+		+		
	H 70	3/4/74	860	+	+	+		+		
	H 68	1/4/74	660	+	+	+		+		
	H 67	31/3/74	520	+	+	+		+		

H	hydrography (salinity/temperature)
O	dissolved oxygen
N	nutrients (phosphate/silicate)
A	alkalinity
S	suspended particulate matter
P	plankton
C	coring.

APPENDIX B

Field laboratory methods

As some analytical methods had to be completed within a short time after sampling and the ship (R/V "Hans Reusch") had no laboratory facilities, it was necessary to establish a laboratory at Lofthus, some 8 km south of the entrance of Sörfjorden.

i) Dissolved oxygen

Dissolved oxygen was measured by the conventional Winkler method (Winkler, 1888).

ii) Dissolved phosphate and silicate

The terms 'dissolved phosphate' and 'dissolved silicate' correspond to 'reactive' P and Si (Strickland and Parsons, 1968).

Phosphate and silicate were determined in unfiltered water samples as described by Strickland and Parsons (1968). Estimated precision for the phosphate method is ± 0.02 µg-at. PO_4-P/l and for the silicate method ± 2 µg-at. SiO_4-Si/l.

A UNICAM SP600 (series 2) spectro-photometer was used for all the determinations, with 4 cm cells for PO_4-P and 1 cm cells for SiO_4-Si.

iii) Filtration

Filtration was carried out during cruise B (August 1971) using a SARTORIUS vacuum filtration system and SARTORIUS membrane filters (composed of cellulose nitrate, pore size = 0.45 µ,

diameter = 47 mm). On other cruises, plexiglas filter-holders and a totally enclosed N_2 gas pressure (~12 psi) filtration system was used (see Spencer et al., 1972). The filter-holders (a series of 4) were fitted with NUCLEPORE membrane filters (composed of a high molecular weight polycarbonate, pore size = 0.4 μ, diameter = 37 mm).

In an attempt to remove any retained seasalt in the particulate matter or within the filter itself, samples obtained on cruises in 1971, 1972 and 1973 were all washed immediately after filtering, with ~100 ml of membrane filtered (0.45 μ), deionized distilled water. After being washed, the filter papers were stored in dry, acid-cleaned petri dishes, in which they were kept until analysed. The filtrate was weighed in order to determine the amount of water filtered. Finally, the pH of the filtrate was lowered to about 2 with 6N ARISTAR HCl.

During Cruise III (April 1974) the treatment of filters was different. Unwashed filters were brought back to Edinburgh and analysed. After chemical analyses they were washed and reanalysed.

Experiments on the performance of various membrane filters have shown that NUCLEPORE filters are recommended for filtration of seawater (Cranston and Buckley, 1972) and are preferred to SARTORIUS membrane filters. They show very small losses in weight after filtering, have a high retention of clay particles (Holmes, pers. comm.) and humic material and retain very small amounts of seasalt (Cranston and Buckley, op. cit.). Experience has also shown

that NUCLEPORE filters do not deteriorate during X-ray exposure.

iv) Eh, pH and alkalinity

Eh and pH were measured in water samples collected during cruise B, August 1971, using an ORION combination platinum electrode and an ACTIVATION combination glass electrode respectively. Titration alkalinity was determined during cruise I, August 1972, using the potentiometric method of Edmond (1970) which involves titrating the sample with HCl in a closed system. Tables of results of Eh, pH and alkalinity measurements are not included in the thesis.

APPENDIX C

Laboratory analytical techniques

This section includes all analytical techniques undertaken at the Grant Institute of Geology in Edinburgh.

i) Sediment preparation

The frozen cores were cut lengthwise with a CLIPPER masonry saw. The newly exposed surface of each half was rinsed clean with tap water. One half was kept frozen as reference material while the other half was subsampled according to colour changes (cruise A and B) or divided into units of 2, 4 or 5 cm length (cruise I). Each sub-sample was dried at 110°C and then ground to a fine powder ($<$ 200 mesh) using a tungsten carbide TEMA disc mill for half the sample (major element analysis) and an agate TEMA disc mill for the other half (trace element analysis).

ii) Sediment mineralogy

The dried, ground sediment powder was mixed into a few drops of acetone and spotted on a glass slide. A PHILIPS X-ray diffractrometer (PW 1011/1050) was employed with Ni filtered Cu radiation (Cu Kα). Each sample was scanned from $4^{\circ} 2\theta$ to $65^{\circ} 2\theta$.

iii) Major elements in sediments

The major elements (Ca, K, Fe, Ti, Al, Si, Mg, P and Mn) were determined by X-ray fluorescence spectrometry

employing an analytical method similar to that described by Rose et al. (1963). With the exception of Mn, which was analysed on a PHILIPS PW 1540 single-channel spectrometer, all the elements were determined using a PHILIPS PW 1212 multi-channel spectrometer.

A mixture of dried sediment ground in the tungsten disc mill (p. 143), lanthanum oxide (heavy absorber) and lithium tetraborate (flux and diluent) in the ratio 1:1:8, was fused at 1050°C for 20 minutes. When cool, the fused beads were made up to their original weight by further addition of $Li_2B_4O_7$, thus compensating for the loss of volatiles. The samples were then reground in a TEMA tungsten carbide disc mill for 2 minutes and redried at 110°C overnight. Finally the samples were pelletised at 15 tons pressure for 1 minute with boric acid as backing material.

Standards (Table C 1) were prepared in an identical manner. The standards and samples were analysed in sets of four, of which one was kept in continually as a monitor, to correct for drift in the machine. Instrument conditions for each element are summarized in Table C 2. The data was processed manually. The analytical precision (6 replicates of one disc) is shown in Table C 3.

iv) Carbonate-C (CO_2) and total-C in sediments

Total-C content was determined by combusting a known weight of dried (110°C), ground sediment in a LECO (Laboratory Equipment Corporation) induction furnace (model 521-200; fitted with a catalyst furnace (model 507-100) and sulphur and dust traps).

Table C 1

Standards used for X-ray fluorescence spectrometry (sediments)

Code	Type of material	Source
	Major element analysis	
E 1	ferrogabbro	Grant Institute of Geology Standard
E 3	fjord sediment	"
88 A	dolomitic limestone	U. S. National Bureau of Standards
QMC I 1	aplitic granite	Queen Mary College, Department of Geology
QMC I 3	dolerite	"
QMC M 3	calc-silicate	"
	Trace element analysis	
G 2	granite	U. S. G. S. Standards
GSP-1	granodiorite	"
DTS-1	dunite	"
G 1	granite	"
W 1	diabase	"
synthetic standards (see text)		

Table C 2

Instrument conditions for X-ray fluorescence analyses (sediments)

Element and line		Machine PW-	Tube	KV	mA	Crystal	Peak	Background(s)	Counter	Counting time (secs)	cycles	coll.	vac.
Ca	K_α	1212	Cr	40	24	PET	45.19		F	10	3	F	yes
K	K_α	1212	Cr	60	24	PET	50.68		F	10	3	C	yes
Fe	K_α	1212	Cr	60	24	LiF(200)	57.60		S	20	3	F	yes
Ti	K_α	1212	Cr	60	24	LiF(200)	86.26		F	10	3	F	yes
Si	K_α	1212	Cr	60	24	PET	109.12		F	20	3	C	yes
Al	K_α	1212	Cr	60	24	PET	144.95		F	20	3	C	yes
Mg	K_α	1212	Cr	40	32	ADP	136.85	133.85	F	100	3	C	yes
P	K_α	1212	Cr	60	24	PET	89.47	87.47	F	40	3	F	yes
Mn	K_α	1540	W	60	24	LiF(200)	63.12		F	20	4	F	yes
Ag	K_α	1212	W	80	24	LiF(200)	15.95	15.6 and 16.40	S	40	3	F	no
Ba	K_α	1212	W	80	24	LiF(200)	10.99	12.00	S	40	3	F	no
Bi	L_α	1212	W	80	24	LiF(200)	33.00	33.50	S	40	3	F	no
Cd	K_α	1212	W	80	24	LiF(200)	15.27	15.00 and 15.60	S	40	3	F	no
Cu	K_α	1212	W	80	24	LiF(200)	45.00	45.80	S	40	3	F	no
In	K_α	1212	W	80	24	LiF(200)	14.61	15.00 and 14.30	S	40	3	F	no
Pb	L_β	1212	W	80	24	LiF(200)	28.23	28.60	S	40	3	F	no
Sb	K_α	1212	W	80	24	LiF(200)	13.40	13.70 and 13.10	S	40	3	F	no
Sn	K_α	1212	W	80	24	LiF(200)	14.00	14.30 and 13.70	S	40	3	F	no
Zn	K_α	1212	W	80	24	LiF(200)	41.76	41.00	S	40	3	F	no
Mo	Compton scattered K_α	1540	Mo	60	24	LiF(200)	21.13		S	constant count (10^5)	5	F	no

Counter: F = flow, S = scintillation

Collimator: F = fine, C = coarse

The amount of CO_2 evolved was measured with a LECO carbon analyser (model 572-100). The analytical procedure is fully described in the LECO instruction manual. The accuracy of the instrument was checket at the beginning of each set of readings using LECO steel rings of known carbon content. The overall precision (6 replicate analyses) is $\pm$5%.

Carbonate-C was determined by acid treatment (HCl) and measurement of CO_2 evolved. Ferrous sulphate was added to the sample to prevent hydrolysis of any organic matter. The overall precision was determined from 6 replicates and was found to be $\pm$4%.

Organic-C was assumed to be equivalent to the difference between total-C and carbonate-C as measured above.

v) Trace elements in sediments

Trace elements (Ag, Ba, Bi, Cd, Cu, In, Pb, Sb, Sn and Zn) in the sediments were analysed by X-ray fluorescence spectrometry (PW 1212) using the method of Reynolds (1963). 4 g of sediment sample (dried at 110°C and ground in an agate TEMA disc mill) was pelletised (p. 144). Their mass absorption coefficients were estimated by measuring the intensities of the Compton-scattered portion of a $Mo_{K\alpha}$ primary beam (for instrument conditions see Table C 2). Standards (Table C 1) of known mass-absorption coefficients and samples were run in a similar way to that described for major element analyses (p. 144).

The spectrometer conditions for the analyses of trace elements are shown in Table C 2. Both international standards

(Table C 1) and synthetic standards were used. The latter were made up to cover the wide range of trace metal concentrations in the sediments. Two dilution series, one composed of Ba, Cu, Pb and Zn with concentrations ranging between 5% and 0.00032% and one series of Ag, Bi, Cd, In, Sb and Sn in the concentration range 1% to 0.00032%, were prepared. As a base shale of known composition was used and to test the effects of highly variable matrices, Fe_2O_3 in the range 5 to 50% was added. The respective metals were all added as 'specpure' oxides. Working curves were linear and the correction of matrix differences was made following Reynolds (1963). There was good agreement between international standards (Table C 1) and synthetic standards.

Precision of analysis is shown in Table C 3.

vi) Total weight of suspended particulate matter

TSM was determined gravimetrically. Preweighed membrane filters were, after returning to Edinburgh, dried in a dessicator and weighed using a 5 places METTLER H20T balance. No great accuracy and precision are attributed to these results, particularly for SARTORIUS membrane filters (cruise B, 1971).

vii) Mineralogy of suspended particulate matter

The mineral constituents were identified by X-ray diffraction (see p. 143 for instrument conditions). The filter papers were prepared by attaching a fragment (~1 x 1 cm) of each to a glass slide with silicone grease.

Table C 3

Analytical precision of X-ray fluorescence analysis of sediments

Element	Analytical precision	Element	Analytical precision
Ca	1%	Ag	5%
K	1%	Ba	7%
Fe	2%	Bi	5%
Ti	2%	Cd	4%
Si	2%	Cu	4%
Al	2%	In	8%
Mg	3%	Pb	5%
P	10%	Sb	6%
Mn	3%	Sn	6%
		Zn	3%

viii) Scanning electron microscopy

An S4 STEROSCAN scanning electron microscope was used for the identification of the constituents of suspended particulate matter. The work was carried out at the Department of Electrical Engineering, Edinburgh, under the supervision of I. Goodall.

ix) Analysis of major elements in particulate matter

The chemical analysis of Ca, K, Fe, Ti, Si, Al, Mg, P, Mn and S was undertaken using a thin film X-ray fluorescence technique (PW 1212 spectrometer). The technique is reported in detail in Taylor (1974), including preparation of standards, presentation of samples and discussion of analytical problems. A less detailed description of the method is given in Price and Calvert (1973), Price (1974a) and Price and Skei (1975) (Appendix E). Only a summary of the technique is included here, where the modification of the original method has been emphasized.

Standards were prepared by suspending known amounts of various rock powders (1-5μ) in distilled water and filtering through NUCLEPORE (or SARTORIUS) membrane filters. The range of standards was such that extrapolation was not necessary. In 1971 and 1972 cellulose discs were placed behind the filters and analysed in the same way as sediments (p. 144). In 1973 and 1974 filters were run without backing discs, and this reduces both the blank and background counts.

Straight line calibration curves were plotted manually for all elements, and the appropriate parameters fed into a program

used to process the data (Edinburgh Regional Computing Centre). To check if all seasalt was removed from the filters by the washing (p. 141), Cl counts were recorded. Normally they were found to be close to the blank counts for Cl, hence no salt correction of Mg, S, Ca and K was required.

Instrument conditions are given in Table C 4 and analytical precision from 6 replicates in Table C 5. The relative deviation between results of different years when computed from the same calibration curves of the same standards is within 10% of the amounts shown.

To test the accuracy of the method, membrane filtered Copenhagen Seawater was spotted on NUCLEPORE filters and analysed for Mg, S and K, using the calibration curves of the ordinary standards. The relative amounts of Mg, S and K found commensurated with the known ratios of these elements in seawater (Price, pers. comm.). The accuracy of the analysis of particulate Mn was checked by comparison with results from Neutron Activation Analyses. These results deviated within 10% at a 10 n g Mn level (Price, pers. comm.)

x) Analysis of Cu, Pb and Zn in particulate matter

These analyses were also undertaken using a thin film X-ray fluorescence technique (PW 1212 spectrometer). The technique is essentially the same as the one outlined above (see also Skei et al., 1973; Price and Skei, 1975, Appendix E). A series of synthetic standards of preweighed deposits of CuO, $PbCrO_4$ and $Zn_2Fe(CN)_6$, all almost insoluble in water, were diluted with shale (p. 148) and suspended in distilled water, followed by filtering through

Table C 4

Instrument conditions for X-ray fluorescence analyses (suspended matter)

Element and line	Tube	KV	mA	Crystal	Peak	Background	Counter	Counting time (secs)	cycles	coll.	vac.
Ca							F	20	3	F	yes
K							F	20	3	C	yes
Fe							F+S	40	3	F	yes
Ti							F	20	3	F	yes
Si	as for sediments (Table C 2)						F	20	3	C	yes
Al							F	40	3	C	yes
Mg							F	100	3	C	yes
P							F	40	3	F	yes
Mn							F	20	3	F	yes
Cu							F+S	40	3	F	yes
Pb							F+S	100	3	F	yes
Zn							F+S	40	3	F	yes
S K_α	W	60	24	PET	75.63	73.42	F	20	3	C	yes

Counter: F = flow, S = scintillation

Collimator: F = fine, C = coarse

Table C 5

Precision of suspended particulate matter and dissolved metal analyses

Element	Analytical precision	Element	Analytical precision
Ca	2%	Cu	15% (15%)
K	2%	Pb	11% (40%)
Fe	1% (10%)	Zn	9% (10%)
Ti	5%		
Si	5%		
Al	2%		
Mg	3%		
P	4%		
Mn	4% (4%)		
S	2%		

( ) = dissolved metals

NUCLEPORE (or SARTORIUS) membrane filters. The standards were in the concentration range 5 to 100 µg metal, and hence lay outside the majority of the samples analysed. No tests on the accuracy of these analyses have been performed. Instrumental conditions and analytical precision are shown in Table C 4 and C 5 respectively.

xi) Dissolved metals in fjord and river/lake waters

Methods involving solvent extraction and Atomic Absorption Spectrometry (A.A.S.) were used to determine the concentration of dissolved Fe, Mn, Cu, Pb and Zn (similar to those of Taylor (1974)).

4 x 400 ml portions of each sample were transferred into 500 ml separating funnels. Aliquots of 0, 1, 2 and 4 ml of a mixed metal standard solution were added to the samples. 10 ml of 6% W/V NaK-tartrate was added to each sample (to keep Fe and Mn in solution at higher pH) and after 10 minutes the pH was raised to just over 6 with 2N A.A.S. grade NH_3. 5 ml of 10% W/V ANALAR sodium diethyl dithiocarbamate (NaDEDTC) was added to each funnel followed by 20 ml of A.A.S. grade 4-methylpentan-2-one (MIBK) after a further 10 minutes. The funnels were shaken for 30 minutes and left to stand for 20 minutes. The bottom aqueous layer was then discarded while the organic layer was run into test-tubes.

The metal contents of the organic solutions were determined with a VARIAN-TECHTRON AA4/5 atomic absorption spectrometer.

Samples of very high Zn content were analysed for Zn

without the preconcentration step by spraying the seawater directly into an air-acetylene flame. Non-atomic absorption was corrected for using a TECHTRON Hydrogen Lamp. This method was found to be satisfactory at Zn levels higher than 50 μg/kg. The effect of seasalt on the absorption was checked by diluting a seawater sample containing $\sim$4000 μg/kg Zn up to 25 times with distilled water. It appeared that the background correction with the H_2 lamp corrected for all molecular absorption.

The analytical precision for the various elements, based on 6 replicates, is given in Table C 5.

xii) Metals in plankton

Plankton was dried at 80°C and decomposed in a mixture of concentrated H_2SO_4, HNO_3 and 50% H_2O_2 in silica crucibles under gentle heating (the siliceous fraction of the plankton was not attacked). To the residue was added a few drops of concentrated HCl and distilled water (10 cc). Samples were analysed for Cd, Cu, Fe, Mn, Pb, and Zn by atomic absorption; correction of molecular absorption was made by using an H_2 lamp (see above). The mixed metal solution used as standards for the analyses of water was also employed in the plankton analyses. Tables of results are not included in the thesis.

APPENDIX D

Chemical data

i) Hydrographic and hydrochemical data (Table D 1)

Density (σ_t) was computed from the temperature and salinity data following the equation outlined in Knudsen's (1901) 'Hydrographic Tables'.

ii) Sediment data (Tables D 2-3)

iii) Suspended particulate matter and dissolved metal data (Tables D 4-7)

Table D 1

Hydrographic and hydrochemical data

Cruise, station and date	Depth (m)	S‰	T°C	σ_T	O_2(ml/l)	phosphate-P (µg-at./l)	silicate-Si (µg-at./l)
Cruise I							
H 35	0	6.00	16.60	3.50		0.24	1.10
Aug 1972	1	8.30	16.20	5.33		-	-
	2	11.50	16.40	7.74		-	-
	3	15.80	15.80	11.14		-	-
	4	16.50	15.80	11.67		-	-
	5	17.80	15.40	12.74		0.24	0.00
	7	26.40	12.80	19.82		-	-
	9	27.40	11.60	20.80		-	-
	10	27.60	11.00	21.05		0.08	1.10
	15	28.30	8.80	21.94		-	-
	20	28.90	7.90	22.53		-	-
	25	29.60	7.00	23.20		0.30	1.60
	30	30.20	6.40	23.74		-	-
	40	31.20	7.20	24.35		-	-
	50	31.40	7.40	24.56		1.02	3.80
	60	31.60	7.50	24.70		-	-
	70	31.80	7.40	24.87		-	-
	80	32.00	7.50	25.01		-	-
	90	32.20	7.10	25.23		-	-
	100					1.10	8.20
	150					1.29	11.50
	200					1.41	13.80
	250					1.13	15.00
	300					1.04	12.20
	350					1.22	14.90
	400					0.99	12.70
	450					0.96	16.00
	500						13.80
	550					0.71	12.00
	575					1.16	10.70
	600					0.94	9.70
	625					0.89	9.30
	650					1.22	9.30
	675					1.21	10.00
	700					0.96	14.90
S 36	0					0.31	4.80
Aug 1972	5					0.37	1.50
	10					0.38	0.60
	15					0.11	0.80
	25					0.75	0.60
	50					2.33	5.70
	75					2.02	7.80
	100					1.87	9.70
	125					1.74	13.00
	150					1.45	13.70
	200					1.42	14.40
	250					1.56	15.50
	300					1.39	14.30
	325					1.44	13.80
	350					1.18	15.30
	375					1.24	15.10
S 41	0	12.10	12.50	9.13		0.15	3.40
Aug 1972	1	12.10	12.60	9.12		-	-
	2	12.10	12.60	9.12		-	-
	3	12.30	12.80	9.25		-	-
	4	12.90	12.80	9.71		-	-
	5	14.80	13.40	11.10		0.15	5.20
	7	19.00	13.10	14.39		-	-
	9	24.30	12.70	18.55		-	-
	10	26.20	12.20	20.20		0.06	0.50
	12.5	27.10	10.00	21.11		-	-
	15	27.40	9.20	21.45		0.00	0.40
	20	28.00	8.00	22.06		-	-
	25	28.50	7.10	22.55		0.45	0.00
	30	29.30	6.40	23.25		-	-
	35	29.90	6.40	23.72		-	-

Table D 1 continued

Cruise, station and date	Depth (m)	S‰	T°C	σ_T	O_2(ml/l)	phosphate-P (µg-at./l)	silicate-Si (µg-at./l)
S 41 (continued)							
	40	30.40	6.40	24.12		-	-
	50	30.90	6.90	24.46		3,77	4.80
	60	31.40	7.10	24.84		-	-
	75	31.70	7.30	25.05		4.17	8.70
	90	32.10	7.20	25.38		-	-
	100					3.73	11.40
	125					2.09	13.60
	150					1.57	16.00
	175					1.57	15.30
	200					1.72	15.70
	225					1.57	16.10
	250					1.37	16.60
	275					1.56	17.50
S 42	0	12.10	13.40	8.72			
Aug 1972	1	12.20	13.40	8.80			
	2	12.25	13.50	8.82			
	3	12.40	13.60	8.92			
	4	12.90	13.80	9.27			
	5	13.00	13.95	9.32			
	7	14.90	14.65	10.65			
	8	16.40	14.15	11.90			
	9	22.80	13.20	16.97			
	10	25.70	12.80	19.28			
	15	27.30	10.30	20.94			
	20	28.00	8.60	21.73			
	25	28.20	7.65	22.02			
	30	28.55	6.80	22.40			
	35	29.50	6.40	23.19			
	40	30.10	6.25	23.68			
	45	30.45	6.30	23.95			
	50	30.70	6.60	24.11			
S 43	0	12.60	13.80	9.04			
Aug 1972	1	12.60	13.90	9.03			
	2	12.50	13.90	8.95			
	3	12.50	13.90	8.95			
	4	12.70	14.00	9.09			
	5	13.10	14.20	9.36			
	6	13.70	14.30	9.80			
	7	18.20	14.20	13.27			
	8	20.60	14.20	15.11			
	9	25.00	12.40	18.81			
	10	26.40	12.00	19.96			
	12.5	27.30	10.50	20.90			
	15	27.60	9.80	21.25			
	20	28.00	8.30	21.78			
	25	28.40	7.20	22.23			
	30	29.00	6.70	22.76			
	35	29.60	6.20	23.30			
	40	30.40	6.40	23.90			
	45	30.70	6.60	24.11			
	50	31.00	6.80	24.32			
S 45	0					-	5.90
Aug 1972	10					0.32	2.10
	25					0.72	0.20
	50					8.13	11.70
	75					4.83	10.50
	100					2.57	12.80
	150					2.00	15.20
	225					1.80	20.20
S 46	0	9.60	12.80	6.89		0.42	6.60
Aug 1972	1	9.80	12.75	7.05		-	-
	2	9.80	12.65	7.07		-	-
	3	10.30	12.65	7.45		-	-
	4	10.90	12.65	7.91		-	-
	5	11.40	12.55	8.31		0.57	6.20

Table D 1 continued

Cruise, station and date	Depth (m)	S‰	T°C	σ_T	O_2(ml/l)	phosphate-P (µg-at./l)	silicate-Si (µg-at./l)
S 46 (continued)							
	6	11.45	12.55	8.35		-	-
	8	11.80	12.65	8.61		-	-
	10	12.40	13.00	9.02		0.27	0.90
	15	20.00	13.50	14.77		0.36	0.00
	16	24.20	12.70	18.14		-	-
	18	26.50	10.90	20.22		-	-
	20	27.10	9.60	20.89		-	-
	25	27.90	7.90	21.75		0.69	2.00
	30	28.40	7.00	22.26		-	-
	35	28.80	6.70	22.61		-	-
	40	29.80	6.40	23.43		-	-
	45	30.20	6.60	23.72		-	-
	50	30.70	6.80	24.09		9.02	11.40
	60	31.20	6.95	24.46		-	-
	65	31.40	7.00	24.61		-	-
	70	31.50	7.00	24.69		-	-
	75	31.60	7.10	24.75		5.07	10.50
	80	31.82	7.20	24.91		-	-
	85	31.90	7.20	24.98		-	-
	90	31.98	7.00	25.07		-	-
	100	-	-	-		3.06	13.40
Cruise II							
S 58	0	18.90	9.70	14.51	7.10		
Sep 1973	1	18.90	9.70	14.51	-		
	2	22.30	9.70	17.15	-		
	3	25.00	10.10	19.18	-		
	4	28.80	10.00	22.15	-		
	5	30.10	10.00	23.16	6.41		
	6	31.00	9.90	23.87	-		
	7	31.10	9.90	23.95	-		
	8	31.30	9.85	24.11	-		
	10	31.45	9.82	24.24	6.15		
	12	31.55	9.80	24.32	-		
	14	31.90	9.75	24.60	-		
	16	32.56	9.70	25.12	-		
	18	32.65	9.75	25.18	-		
	20	32.57	9.65	25.14	5.89		
	25	32.66	9.60	25.21	5.91		
	30	33.00	8.20	25.70	5.72		
	35	33.40	7.40	26.13	-		
	40	33.61	7.19	26.32	-		
	45	33.87	7.05	26.54	-		
	50	34.04	6.95	26.69	5.62		
	55	34.38	6.95	26.96	-		
	60	34.42	7.00	26.98	-		
	65	34.36	6.95	27.10	-		
	70	34.68	6.90	27.20	5.49		
	75	34.75	6.90	27.26	-		
	80	34.81	6.85	27.31	5.28		
	85	34.86	6.80	27.36	-		
	90	34.95	6.80	27.42	5.00		
	95	35.01	6.80	27.47	-		
	100				4.66		
	125				5.01		
	150				4.77		
	200				5.00		
	225				5.00		
	250				5.00		
S 59	0	18.40	9.83	14.10	7.04	2.07	4.50
Sep 1973	1	20.20	10.10	15.46	-	-	-
	2	26.00	10.80	-	-	-	-
	3	29.70	10.50	22.77	5.77	-	-
	4	30.50	10.00	23.47	-	-	-
	5	30.55	10.00	23.51	-	-	-
	6	30.70	10.00	23.62	-	-	-

Table D 1 continued

Cruise, station and date	Depth (m)	S‰	T°C	σ_T	O_2(ml/l)	phosphate-P (µg-at./l)	silicate-Si (µg-at./l)
S 59 (continued)							
	8	31.10	10.00	23.93	6.18	0.00	6.40
	10	31.60	9.90	24.34	-	-	-
	12	31.80	9.90	24.50	-	-	-
	15	31.95	9.80	24.63	-	-	-
	20	32.10	9.60	24.78	5.76	0.08	6.30
	25	32.46	9.20	25.12	-	-	-
	30	32.54	8.50	25.29	-	-	-
	35	32.76	7.90	25.55	-	-	-
	40	33.35	7.30	26.10	-	-	-
	45	33.60	7.00	26.34	-	-	-
	50	33.90	6.90	26.59	4.95	2.67	6.70
	55	34.11	6.85	26.76	-	-	-
	60	34.33	6.80	26.94	-	-	-
	65	34.44	6.78	27.03	-	-	-
	70	34.54	6.70	27.12	-	-	-
	75	34.70	6.61	27.26	4.18	3.10	9.90
	80	34.82	6.70	27.34	-	-	-
	85	34.91	6.70	27.41	-	-	-
	90	34.95	6.65	27.45	-	-	-
	95	35.00	6.60	27.49	-	-	-
	100				4.07	2.03	21.10
	150				4.27	1.37	18.90
	200				3.93	1.11	14.90
	250				3.77	1.24	19.40
	300				4.17	1.23	20.90
	310				4.38	-	-
	330				4.39	-	-
	350				4.33	1.27	21.50
	385				4.54	1.37	23.70
S 60	0	20.80	10.20	15.91			
Sep 1973	1	20.80	10.20	15.91			
	2	25.70	10.30	19.69			
	3	28.90	10.20	22.19			
	4	29.30	10.20	22.50			
	5	29.90	10.30	22.95			
	6	29.90	10.30	22.95			
	7	29.90	10.30	22.95			
	8	30.10	10.40	23.09			
	9	30.40	10.40	23.32			
	10	30.40	10.40	23.32			
	12	30.50	10.40	23.40			
	14	30.70	10.50	23.54			
	16	31.00	10.40	23.79			
	18	31.05	10.40	23.83			
	20	31.50	10.20	24.21			
	25	31.90	10.10	24.54			
	30	32.20	9.95	24.80			
	35	32.40	9.95	24.95			
	40	32.50	9.80	25.06			
	45	32.65	9.42	25.24			
	50	32.67	9.30	25.27			
	55	32.87	8.78	25.51			
	60	33.03	8.40	25.69			
	65	33.10	7.90	25.82			
	70	33.19	7.50	25.95			
	75	33.47	7.20	26.21			
	80	33.59	7.10	26.32			
	85	33.75	6.95	26.46			
	90	33.94	6.95	26.61			
	95	34.14	6.90	26.78			
S 61	0	15.80	9.20	12.16			
Sep 1973	1	20.70	10.40	15.81			
	2	27.10	10.80	20.70			
	3	29.00	10.50	22.22			
	4	29.60	10.20	22.74			

Table D 1 continued

5

Cruise, station and date	Depth (m)	S‰	T°C	σ_T	O_2(ml/l)	phosphate-P (µg-at./l)	silicate-Si (µg-at./l)
S 61 (continued)							
	5	29.80	10.10	22.91			
	6	29.90	10.15	22.98			
	7	30.00	10.20	23.05			
	8	30.20	10.20	23.20			
	9	30.45	10.35	23.37			
	10	30.70	10.35	23.57			
	12	30.85	10.20	23.71			
	14	31.05	10.10	23.88			
	16	31.45	9.95	24.21			
	18	31.75	9.90	24.46			
	20	32.00	9.90	24.65			
	25	32.20	9.70	24.84			
	30	32.35	9.30	25.02			
	35	32.64	8.95	25.30			
	40	32.71	8.10	25.48			
	45	33.00	7.60	25.78			
	50	33.37	7.30	26.12			
	55	33.38	7.00	26.17			
	60	33.96	6.90	26.64			
	65	34.13	6.80	26.78			
	70	34.31	6.80	26.92			
	75	34.45	6.80	27.03			
	80	34.58	6.70	27.15			
	85	34.69	6.70	27.24			
	90	34.76	6.80	27.28			
	95	34.74	6.65	27.28			
S 62 Sep 1973	0	19.30	9.40	14.86			
	1	24.90	10.40	19.06			
	2	28.90	10.80	22.09			
	3	29.60	10.60	22.67			
	4	30.30	10.25	23.27			
	5	30.45	10.10	23.41			
	6	30.50	10.10	23.45			
	7	30.55	10.00	23.51			
	8	30.75	10.00	23.66			
	9	30.80	10.00	23.70			
	10	31.00	10.00	23.86			
	12	31.10	9.95	23.94			
	14	31.10	9.95	23.94			
	16	31.40	9.90	24.18			
	18	31.45	9.90	24.22			
	20	31.50	9.90	24.26			
	25	31.70	9.70	24.45			
	30	32.00	9.18	24.77			
	35	32.20	8.90	24.97			
	40	32.45	8.70	25.19			
	45	32.43	7.90	25.29			
	50	32.64	7.55	25.51			
	55	32.86	7.50	25.69			
	60	33.00	7.40	25.81			
	65	33.30	7.10	26.09			
	70	33.53	7.00	26.28			
	75	33.85	6.90	26.55			
	80	33.93	6.90	26.61			
	85	34.05	6.80	26.72			
	90	34.27	6.70	26.91			
	95	34.42	6.70	27.02			
S 63 Sep 1973	0	18.80	9.20	14.49	6.66	2.87	3.50
	1	26.00	10.00	19.97	-	-	-
	2	29.40	10.50	22.53	-	-	-
	3	29.90	10.60	22.90	-	-	-
	4	30.10	10.30	23.11	-	-	-
	5	30.30	10.10	23.30	-	0.17	2.04
	6	30.40	10.10	23.37	-	-	-

Table D 1 continued

Cruise, station and date	Depth (m)	S‰	T°C	σ_T	O_2(ml/l)	phosphate-P (µg-at./l)	silicate-Si (µg-at./l)
S 63 (continued)							
	7	30.50	10.10	23.45	-	-	-
	8	30.60	10.05	23.54	-	-	-
	9	30.70	10.00	23.62	-	-	-
	10	30.70	10.00	23.62	6.24	0.14	3.79
	12	31.00	10.00	23.86	-	-	-
	14	31.10	9.95	23.94	-	-	-
	16	31.30	9.95	24.10	-	-	-
	18	31.40	9.80	24.20	-	-	-
	20	31.50	9.95	24.30	5.53	-	-
	25	31.70	8.90	24.58	-	-	-
	30	32.10	8.30	24.98	5.02	7.01	7.19
	35	32.45	7.95	25.30	-	-	-
	40	32.64	7.55	25.51	4.25	7.52	-
	45	33.03	7.20	25.86	-	-	-
	50	33.40	7.05	26.17	4.13	12.26	8.65
	55	33.65	7.00	26.38	-	-	-
	60	33.84	6.90	26.54	-	10.02	11.90
	65	34.00	6.90	26.67	-	-	-
	70	34.14	6.80	26.79	3.35	14.10	-
	75	34.22	6.80	26.85	-	-	-
	80	34.39	6.70	27.00	3.68	11.69	15.84
	85	34.51	6.70	27.09	-	-	-
	90	34.56	6.65	27.14	4.23	-	13.61
	95	34.70	6.65	27.25	-	-	-
	100				2.97	5.65	13.41
	110				3.61	3.07	14.97
	130				2.94	2.36	14.19
S 64	0	12.20	9.00	9.38	5.98	15.51	3.89
Sep 1973	1	25.80	10.30	19.77	-	-	-
	2	29.10	10.30	22.33	-	-	-
	3	29.90	10.10	22.99	-	-	-
	4	30.10	10.10	23.14	-	-	-
	5	30.45	10.30	23.38	-	5.20	3.89
	6	30.50	10.20	23.44	-	-	-
	7	30.60	10.10	23.54	-	-	-
	8	30.65	10.20	23.55	-	-	-
	9	30.70	10.10	23.61	-	-	-
	10	30.70	10.10	23.61	-	3.32	2.33
	12	30.95	10.00	23.82	-	-	-
	14	31.00	10.00	23.86	-	-	-
	16	31.05	9.70	23.94	-	-	-
	18	31.20	9.80	24.04	-	-	-
	20	31.45	9.20	24.33	5.44	5.35	6.03
	25	31.70	8.25	24.67	-	-	-
	30	32.00	8.00	24.98	3.65	16.88	14.19
	35	32.20	7.80	25.13	-	-	-
	39	32.40	7.80	25.29	3.49	>25	20.31
H 65	0	27.00	10.10	20.73	6.41	0.07	3.03
Sep 1973	1	27.00	10.05	20.74	-	-	-
	2	27.20	10.19	20.88	-	-	-
	3	27.80	10.19	21.34	-	-	-
	4	28.00	10.02	21.52	-	-	-
	5	28.20	10.10	21.67	5.97	0.10	2.37
	6	28.55	10.10	21.94	-	-	-
	7	28.60	10.10	21.98	-	-	-
	8	28.80	10.20	22.12	-	-	-
	9	29.00	10.20	22.27	-	-	-
	10	29.10	10.20	22.35	-	0.08	3.51
	12	30.45	10.80	23.30	-	-	-
	14	31.00	11.00	23.69	-	-	-
	16	31.60	11.30	24.10	-	-	-
	18	32.05	11.20	24.47	-	-	-
	20	32.10	11.30	24.49	-	-	-
	25	32.35	11.20	24.70	5.26	0.05	2.56

Table D 1 continued 7

Cruise, station and date	Depth (m)	S‰	T°C	σ_T	O_2(ml/l)	phosphate-P (µg-at./l)	silicate-Si (µg-at./l)
H 65 (continued)							
	30	32.50	11.19	24.82	-	-	-
	35	32.75	10.90	25.06	-	-	-
	40	32.91	11.00	25.17	-	-	-
	45	32.96	10.61	25.28	-	-	-
	50	33.02	10.42	25.36	5.61	0.06	3.98
	55	33.16	10.25	25.50	-	-	-
	60	33.35	9.50	25.77	-	-	-
	65	33.50	8.80	26.00	-	-	-
	70	33.70	7.60	26.33	-	-	-
	75	33.94	7.20	26.58	-	-	-
	80	34.07	7.08	26.70	-	-	-
	85	34.32	7.00	26.90	-	-	-
	90	34.45	7.00	27.01	-	-	-
	95	34.60	7.00	27.12	-	-	-
	100				4.52	1.04	6.92
	200				4.00	1.02	13.46
	250				4.71	1.06	13.75
	300				4.92	0.95	12.89
	350				4.84	1.01	14.41
	400				-	1.06	15.07
	450				4.45	0.89	13.18
	500				4.35	0.99	14.22
	550				4.49	1.02	14.31
	600				5.32	0.88	13.37
	650				5.38	0.93	14.13
	700				5.21	1.65	13.75
Cruise III							
H 67	0	31.40	5.75	24.77	8.01	0.00	0.68
Mar 1974	0.5	31.40	5.75	24.77	-	-	-
	1	31.40	5.75	24.77	-	-	-
	1.5	31.40	5.75	24.77	-	-	-
	2	31.40	5.74	24.77	-	-	-
	3	31.40	5.70	24.77	-	-	-
	4	31.40	5.70	24.77	-	-	-
	5	31.50	5.55	24.87	7.92	0.07	0.00
	6	31.55	5.50	24.91	-	-	-
	7	31.55	5.50	24.91	-	-	-
	8	31.60	5.30	24.97	-	-	-
	9	31.65	5.20	25.02	-	-	-
	10	31.70	5.15	25.07	7.97	0.00	1.56
	12	31.70	5.10	25.07	-	-	-
	14	31.70	5.00	25.09	-	-	-
	16	31.80	4.97	25.17	-	-	-
	18	31.80	4.87	25.18	-	-	-
	20	31.85	4.80	25.23	-	-	-
	25	32.15	5.10	25.43	7.19	0.06	0.39
	30	32.37	5.00	25.62	-	-	-
	35	32.90	5.15	26.02	-	-	-
	40	33.60	6.70	26.38	-	-	-
	45	34.25	7.80	26.74	-	-	-
	50	34.49	8.15	26.87	6.00	0.58	5.15
	55	34.61	8.21	26.96	-	-	-
	60	34.68	8.22	27.01	-	-	-
	65	34.83	8.20	27.13	-	-	-
	70	34.90	8.18	27.19	-	-	-
	75	34.95	7.99	27.26	-	-	-
	80	34.99	7.82	27.31	-	-	-
	85	35.03	7.80	27.35	-	-	-
	90	35.05	7.70	27.38	-	-	-
	95	35.07	7.60	27.41	-	-	-
	100				5.95	0.59	9.23
	150				6.14	0.59	5.93
	200				6.03	0.71	11.18
	250				6.10	0.66	5.73
	300				5.84	0.64	8.16

Table D 1 continued

8

Cruise, station and date	Depth (m)	S‰	T°C	σ_T	O_2(ml/l)	phosphate-P (µg-at./l)	silicate-Si (µg-at./l)
H 67 (continued)							
	400				5.51	0.80	11.28
	425				5.49	0.80	13.12
	450				5.73	0.89	13.80
	475				5.73	0.84	13.80
	490				5.41	0.86	12.44
H 68	0	31.25	5.75	24.65	7.92	0.05	1.98
Apr 1974	0.5	31.30	5.75	24.69	-	-	-
	1	31.35	5.70	24.73	-	-	-
	1.5	31.35	5.65	24.74	-	-	-
	2	31.40	5.62	24.78	-	-	-
	3	31.40	5.60	24.78	-	-	-
	4	31.45	5.60	24.82	-	-	-
	5	31.45	5.60	24.82	7.82	0.06	0.69
	6	31.50	5.60	24.86	-	-	-
	7	31.55	5.60	24.92	-	-	-
	8	31.55	5.60	24.90	-	-	-
	9	31.55	5.50	24.91	-	-	-
	10	31.55	5.50	24.91	7.92	-	-
	12	31.55	5.50	24.91	-	-	-
	14	31.60	5.75	24.92	-	-	-
	16	31.60	5.70	24.93	-	-	-
	18	31.60	5.70	24.93	-	-	-
	20	31.65	5.30	25.01	-	-	-
	25	32.11	5.20	25.39	7.16	0.27	1.79
	30	32.63	5.55	25.76	-	-	-
	35	33.02	6.10	26.00	-	-	-
	40	33.50	6.70	26.30	-	-	-
	45	33.71	6.89	26.44	-	-	-
	50	33.84	7.20	26.50	5.92	0.67	5.46
	55	33.86	7.22	26.51	-	-	-
	60	34.10	7.60	26.65	-	-	-
	65	34.51	8.10	26.89	-	-	-
	70	34.62	8.19	26.97	-	-	-
	75	34.70	8.21	27.11	-	-	-
	80	34.80	8.20	27.11	-	-	-
	85	34.89	8.15	27.18	-	-	-
	90	34.97	8.00	27.27	-	-	-
	95	35.04	8.00	27.33	-	-	-
	100				5.61	0.89	17.46
	150				5.82	0.77	31.84
	200				5.66	0.91	16.96
	300				5.45	0.97	24.70
	350				5.83	-	-
	400				5.78	-	-
	450				5.44	0.95	31.84
	500				5.24	0.92	42.76
	550				5.41	-	-
	600				5.66	0.95	31.05
	640				5.50	0.97	17.96
S 69	0	31.20	6.90	24.47	5.53	0.19	1.88
Apr 1974	0.5	31.25	6.80	24.52	-	-	-
	1	31.25	6.80	24.52	-	-	-
	1.5	31.25	6.75	24.52	-	-	-
	2	31.28	6.73	24.55	-	-	-
	3	31.29	6.70	24.56	-	-	-
	4	31.31	6.50	24.60	-	-	-
	5	31.45	6.18	24.75	6.97	-	1.69
	6	31.55	6.30	24.82	-	-	-
	7	31.80	6.10	25.04	-	-	-
	8	31.80	6.00	25.05	-	-	-
	9	32.00	5.90	25.22	-	-	-
	10	32.00	5.90	25.22	6.32	0.15	0.60
	12	32.10	5.70	25.32	-	-	-
	14	32.10	5.65	25.33	-	-	-
	16	32.16	5.70	25.37	-	-	-
	18	32.34	5.80	25.50	-	-	-

Table D 1 continued

9

Cruise, station and date	Depth (m)	S‰	T°C	σ_T	O_2(ml/l)	phosphate-P (µg-at./l)	silicate-Si (µg-at./l)
S 69 (continued)							
	20	32.40	5.82	25.55	-	-	-
	25	32.50	6.00	25.60	6.36	-	0.69
	30	33.02	6.60	25.94	-	-	-
	35	33.30	6.95	26.11	-	-	-
	40	33.48	7.10	26.23	-	-	-
	45	34.02	7.70	26.57	-	-	-
	50	34.52	7.90	26.93	4.79	2.30	6.25
	55	34.56	7.90	26.96	-	-	-
	60	34.68	7.87	27.06	-	-	-
	65	34.73	7.72	27.12	-	-	-
	70	34.77	7.67	27.16	-	-	-
	75	34.82	7.64	27.21	-	-	-
	80	34.86	7.60	27.24	-	-	-
	85	34.92	7.60	27.29	-	-	-
	90	34.92	7.59	27.31	-	-	-
	95	34.95	7.57	27.32	-	-	-
	100				3.53	1.39	10.22
	150				5.06	1.09	11.61
	200				3.85	1.12	12.90
	250				4.67	-	14.28
	300				4.38	1.36	18.15
	325				4.19	-	21.03
	340				4.14	1.47	21.13
H 70 Apr 1974	0	31.70	5.90	24.98	6.90	0.15	0.98
	0.5	31.70	5.90	24.98	-	-	-
	1	31.75	5.85	25.03	-	-	-
	1.5	31.80	5.75	25.08	-	-	-
	2	31.84	5.75	25.11	-	-	-
	3	31.86	5.75	25.13	-	-	-
	4	31.86	5.70	25.13	-	-	-
	5	31.89	5.70	25.16	6.96	0.15	0.29
	6	31.89	5.70	25.16	-	-	-
	7	31.89	5.65	25.16	-	-	-
	8	31.92	5.65	25.19	-	-	-
	9	31.95	5.65	25.21	-	-	-
	10	31.95	5.65	25.21	7.67	0.16	0.10
	12	31.97	5.65	25.23	-	-	-
	14	31.99	5.65	25.24	-	-	-
	16	32.09	5.65	25.32	-	-	-
	18	32.20	5.60	25.41	-	-	-
	20	32.45	5.80	25.59	-	-	-
	25	32.90	6.20	25.89	6.69	0.54	1.28
	30	33.15	6.38	26.07	-	-	-
	35	33.31	6.75	26.14	-	-	-
	40	33.53	7.01	26.28	-	-	-
	45	33.89	7.39	26.51	-	-	-
	50	34.53	8.10	26.91	5.66	1.04	5.70
	55	34.64	8.19	26.98	-	-	-
	60	34.69	8.10	27.04	-	-	-
	65	34.74	8.00	27.09	-	-	-
	70	34.84	7.95	27.18	-	-	-
	75	34.90	7.90	27.23	-	-	-
	80	34.96	7.37	27.30	-	-	-
	85	35.00	7.70	27.34	-	-	-
	90	35.05	7.70	27.38	-	-	-
	95	35.08	7.70	27.40	-	-	-
	100				5.34	1.00	8.36
	200				5.65	0.95	10.12
	300				5.29	1.05	13.37
	350				5.56	1.00	12.39
	400				5.36	1.07	13.07
	450				5.18	-	-
	500				5.28	1.09	13.86

Table D 1 continued

Cruise, station and date	Depth (m)	S‰	T°C	σ_T	O_2(ml/l)	phosphate-P (µg-at./l)	silicate-Si (µg-at./l)
H 70 (continued)							
	550				5.87	1.01	13.07
	600				5.43	1.09	14.84
	650				5.41	1.05	15.24
	700				5.30	1.10	13.47
	725				5.48	-	-
	750				5.51	1.05	14.35
	775				4.83	1.06	14.55
	825				4.90	1.01	15.43
S 71	0	26.70	6.60	20.97	7.32	0.49	1.16
Apr 1974	0.5	27.80	6.75	21.82	-	-	-
	1	29.70	6.70	23.31	-	-	-
	1.5	30.30	6.70	23.79	-	-	-
	2	30.90	6.50	24.28	-	-	-
	3	31.55	6.38	24.81	-	-	-
	4	31.95	6.10	25.16	-	-	-
	5	32.12	6.00	25.30	6.62	0.13	3.68
	6	32.15	6.00	25.33	-	-	-
	7	32.20	5.88	25.38	-	-	-
	8	32.24	5.88	25.41	-	-	-
	9	32.26	5.80	25.44	-	-	-
	10	32.28	5.83	25.45	7.59	0.15	0.39
	12	32.32	5.87	25.48	-	-	-
	14	32.36	5.86	25.51	-	-	-
	16	32.39	5.88	25.53	-	-	-
	18	32.45	5.99	25.56	-	-	-
	20	32.54	6.02	25.63	-	-	-
	25	32.80	6.35	25.79	6.46	0.81	0.00
	30	33.04	6.43	25.97	-	-	-
	35	33.28	6.70	26.13	-	-	-
	40	33.58	7.10	26.31	-	-	-
	45	34.05	7.50	26.62	-	-	-
	50	34.55	7.95	26.95	5.15	4.14	5.52
	55	34.60	7.90	27.00	-	-	-
	60	34.73	7.85	27.13	-	-	-
	65	34.84	7.70	27.20	-	-	-
	70	34.89	7.52	27.24	-	-	-
	75	34.95	7.45	27.29	-	-	-
	80	35.00	7.45	27.34	-	-	-
	85	35.05	7.45	27.38	-	-	-
	90	35.07	7.41	27.42	-	-	-
	95	35.10	7.42	27.46	-	-	-
	100				4.56	1.62	10.94
	150				4.49	1.38	12.87
	200				4.20	1.40	14.91
	250				3.54	-	-
	300				4.27	1.40	18.59
	350				3.89	-	-
	375				2.95	1.60	21.68
S 72	0	18.00	6.20	14.19	7.37	1.42	3.96
Apr 1974	0.5	22.50	6.40	17.70	-	-	-
	1	26.90	6.40	21.15	-	-	-
	1.5	30.50	7.15	23.88	-	-	-
	2	31.50	7.02	24.69	-	-	-
	3	32.05	6.59	25.17	-	-	-
	4	32.12	6.40	25.25	-	-	-
	5	32.14	6.23	25.29	8.26	0.60	0.39
	6	32.11	6.19	25.27	-	-	-
	7	32.20	6.16	25.35	-	-	-
	8	32.25	6.15	25.39	-	-	-
	9	32.29	6.06	25.43	-	-	-
	10	32.30	6.03	25.44	4.27	0.45	0.00
	12	32.35	6.06	25.48	-	-	-
	14	32.42	6.16	25.52	-	-	-
	16	32.50	6.23	25.57	-	-	-
	18	32.65	6.40	25.67	-	-	-

Table D 1 continued

Cruise, station and date	Depth (m)	S‰	T°C	σ_T	O_2(ml/l)	phosphate-P (µg-at./l)	silicate-Si (µg-at./l)
S 72 (continued)							
	20	32.72	6.60	25.70	-	-	-
	25	32.95	6.80	25.85	4.48	3.62	0.68
	30	33.12	7.00	25.96	-	-	-
	35	33.37	7.20	26.13	-	-	-
	40	33.60	7.30	26.30	-	-	-
	45	33.85	7.52	26.46	-	-	-
	50	34.19	7.60	26.72	4.45	8.18	6.31
	55	34.33	7.70	26.81	-	-	-
	60	34.55	7.70	26.99	-	-	-
	65	34.70	7.65	27.11	-	-	-
	70	34.80	7.50	27.24	-	-	-
	75	34.89	7.47	27.29	3.09	2.69	7.95
	80	34.98	7.45	27.36	-	-	-
	85	35.00	7.42	27.38	-	-	-
	90	35.05	7.44	27.42	-	-	-
	95	35.07	7.44	27.43	-	-	-
	100				2.27	2.13	10.67
	105				2.49	1.90	13.29
S 73	0	9.60	7.60	7.48			
Apr 1974	0.5	19.80	7.80	15.44			
	1	21.80	7.80	17.00			
	1.5	28.00	7.50	21.88			
	2	30.20	7.60	23.59			
	3	31.80	7.20	24.90			
	4	32.15	6.80	25.23			
	5	32.18	6.70	25.26			
	6	32.26	6.60	25.34			
	7	32.21	6.40	25.32			
	8	32.30	6.40	25.39			
	9	32.30	6.37	25.40			
	10	32.31	6.30	25.42			
	12	32.40	6.40	25.47			
	14	32.52	6.55	25.55			
	16	32.58	6.60	25.59			
	18	32.60	6.60	25.61			
	20	32.65	6.80	25.62			
	25	32.80	6.80	25.74			
	30	32.90	6.92	25.80			
	35	33.17	7.15	25.98			
	40	33.40	7.21	26.15			
	45	33.71	7.40	26.37			
	50	34.24	7.50	26.77			

Table D 2

Chemical composition of sediments

Major elements (in weight %)

Cruise, date and station	Depth (m)	Ca	K	Fe	Ti	Si	Al	Mg	P	Mn	Total-C	CO_2	Organic-C
Cruise A April 1971													
S 2	0-6	22.18	0.89	26.58	0.17	9.23	2.81	0.31	0.150	0.040	11.18		
S 6	0-2	6.26	2.30	5.34	0.43	22.42	6.10	1.35	0.134	0.084	4.96		
	8.5-10	13.63	1.47	6.86	0.27	14.10	4.03	0.83	0.291	0.074	10.26		
S 7	0-2.5	15.72	1.39	5.73	0.24	11.98	3.76	0.96	0.291	0.070	9.14		
	6-9	3.75	2.71	6.94	0.52	21.79	6.55	1.81	0.159	0.098	3.52		
S 8	0-5	10.48	1.64	7.83	0.29	13.96	4.13	1.07	0.239	0.073	7.42		
	5-7	2.25	2.95	7.09	0.55	22.85	7.05	2.04	0.078	0.101	2.50		
S 10	0-2	14.47	1.25	7.30	0.21	10.67	3.24	0.50	0.255	0.063	10.00		
	8-10	1.90	2.89	6.13	0.61	26.85	7.42	1.88	0.078	0.097	1.83		
S 11	0-2	5.79	1.81	10.06	0.37	18.56	4.69	0.98	0.255	0.071	4.25		
	7-9	1.86	3.08	6.55	0.60	25.01	7.26	2.00	0.078	0.099	1.71		
S 12	0-3.5	1.16	0.80	26.70	0.16	7.46	2.40	0.67	0.422	0.275	3.00		
	3.5-4	0.66	0.70	31.52	0.13	6.46	2.01	0.43	0.332	0.125	1.61		
	5.8-6.3	0.57	0.78	25.40	0.15	7.44	2.42	0.53	0.151	0.222	1.53		
	6.3-12.3	1.67	2.71	5.48	0.51	28.98	6.98	1.12	0.057	0.089	1.14		
S 14	0-6	12.12	0.73	10.75	0.20	9.45	2.55	0.71	0.711	0.086	8.63		
	6-10.5	2.23	3.13	6.95	0.65	26.49	7.28	2.00	0.099	0.098	1.21		
S 15	0-3	2.58	1.92	8.51	0.57	26.21	5.89	0.57	0.136	0.090	1.51		
	10-15	2.62	2.06	4.13	0.69	32.04	6.38	1.30	0.145	0.079	0.46		
S 16	0-4	0.79	0.54	34.51	0.11	4.63	1.47	0.27	0.021	0.121	1.28		
S 19	0-2	3.76	2.13	8.45	0.47	19.66	5.97	1.76	0.136	0.091	3.59		
	8.5-10	2.34	2.62	6.36	0.65	26.68	7.26	1.91	0.103	0.099	1.44		
S 20	6.5-8	2.29	2.39	5.60	0.59	26.99	7.20	1.75	0.103	0.088	1.83		
S 21	0-2.5	2.92	2.30	8.38	0.49	20.46	6.55	1.90	0.151	0.098	3.66		

Table D 2 continued

Cruise, date and station	Depth (m)	Major elements (in weight %) Ca	K	Fe	Ti	Si	Al	Mg	P	Mn	Total-C	CO_2	Organic-C
Cruise A (continued) April 1971													
S 22	0-6.5	2.55	2.14	5.77	0.58	26.14	6.65	2.06	0.090	0.159	1.44		
	6.5-10	2.50	2.28	6.03	0.62	26.78	7.13	2.09	0.074	0.093	1.27		
S 23	0-8	1.99	2.66	6.46	0.52	22.49	7.16	2.30	0.103	0.119	1.97		
Cruise B August 1971													
S 24	0-1.5	1.84	3.02	5.66	0.50	26.00	7.89	2.04	0.095	0.104	1.54		
	1.5-5	1.82	2.97	5.60	0.49	25.89	7.80	1.99	0.069	0.098	1.23		
S 25	0-1.5	2.33	2.31	5.78	0.49	23.39	7.14	2.44	0.100	0.112	-	-	-
	1.5-3	2.40	2.32	5.80	0.51	24.49	7.54	2.47	0.097	0.112	1.18	0.06	1.16
	3-8	2.40	2.30	5.86	0.53	24.99	7.58	2.35	0.070	0.111	1.24	0.06	1.21
	8-12	1.87	3.16	6.41	0.56	26.92	7.33	1.60	0.071	0.095	0.97	n. d.	0.97
	12-15	1.94	3.33	6.90	0.59	27.85	7.62	1.68	0.067	0.089	0.66	n. d.	0.66
	15-20	1.84	3.46	6.32	0.53	25.86	7.36	1.15	0.054	0.091	0.55	n. d.	0.55
	20-25	2.15	2.69	5.18	0.60	30.69	7.03	1.29	0.086	0.084	0.82	n. d.	0.82
	25-30	2.17	2.62	4.88	0.61	31.30	6.97	1.28	0.083	0.082	0.84	n. d.	0.84
	30-35	2.12	2.57	4.88	0.59	30.31	6.67	0.80	0.075	0.082	0.81	0.01	0.81
	35-40	2.30	2.72	5.13	0.60	30.97	7.34	1.34	0.066	0.076	0.82	0.01	0.82
	40-45	2.08	2.67	4.78	0.56	30.16	7.02	1.28	0.073	0.082	0.83	0.03	0.83
	45-50	2.17	2.59	5.60	0.52	27.39	7.63	2.07	0.082	0.102	0.97	0.02	0.97
	50-55	2.19	2.62	5.95	0.53	27.01	7.99	2.18	0.079	0.115	0.97	0.04	0.96
S 31	0-2	1.74	0.45	20.57	0.09	3.72	1.26	0.39	0.127	0.090	3.83		
	2-5.5	1.80	0.66	32.07	0.14	6.23	1.97	0.49	0.133	0.118	2.36		
	5.5-8	1.87	3.15	6.62	0.50	26.45	7.27	1.63	0.055	0.091	1.13		

Table D 3

Chemical composition of sediments

Trace elements (in ppm) Mn (in wt.%)

Cruise, station and date	Depth (m)	Cu	Pb	Zn	Mn
Cruise B August 1971					
S 24	0-1.5	20	47	195	-
	1.5- 5	12	33	149	-
	5-10	12	18	124	-
	10-15	7	18	103	-
S 25	0- 2	50	239	393	-
	2- 3	50	100	260	-
	3- 8	37	32	159	-
	8-12	64	142	800	-
	12-15	33	68	455	-
Cruise I August 1972					
S 36	0- 2	45	212	429	0.155
	2- 4	62	236	477	-
	4- 6	48	161	382	-
	6-10	31	48	207	-
	10-15	30	45	180	-
S 39	0- 2	237	195	447	0.131
	2- 4	189	151	361	-
	4- 6	133	103	265	-
	6-10	84	77	187	-
	10-15	88	71	190	-
	15-20	62	54	149	-
	20-25	55	52	134	-
	25-30	54	56	133	-
	30-35	58	52	139	-
	35-40	56	50	138	-
	40-45	68	54	149	-
	45-50	65	56	148	-
	50-55	69	51	157	-
	55-60	69	54	160	-
S 40	0- 2	174	148	340	0.102
	2- 4	123	108	253	-
	4- 6	84	72	184	-
	6-10	73	62	160	-
	10-15	62	54	147	-

Table D 3 continued

Cruise, station and date	Depth (m)	Cu	Pb	Zn	Mn
Cruise I (continued) August 1972					
S 41	0- 2	115	642	1068	0.146
	2- 4	128	652	1107	-
	4- 6	108	518	981	-
	6-10	48	193	477	-
	10-15	92	61	190	-
S 42	0- 2	307	199	567	0.191
	2- 4	224	150	421	-
	4- 6	181	114	342	-
	6-10	116	71	239	-
	10-15	68	53	150	-
S 43	0- 2	208	258	530	0.245
	2- 4	59	169	385	-
	4- 6	30	101	332	-
	6-10	31	45	223	-
	10-15	27	24	159	-
H 47	0- 2	7	64	172	0.081
	2- 4	7	24	130	-
	4- 6	42	52	118	-
H 48	0- 2	79	69	177	0.190
	2- 4	98	83	205	-
	4- 6	73	62	170	-
	6-10	113	100	236	-
	10-15	71	61	159	-
H 49	0- 2	138	140	269	0.101
	2- 4	75	67	163	-
	4- 6	55	52	136	-
	6-10	51	48	125	-
	10-15	50	49	126	-
S 51	0- 2	74	302	659	0.177
	2- 4	60	233	512	-
	4- 6	135	94	261	-
	6-10	24	12	138	-
S 52	0- 2	177	141	347	0.216
	2- 4	55	235	473	-
	4- 6	49	153	393	-
	6-10	21	21	168	-
	10-15	24	15	124	-
S 56	0- 2	91	747	953	0.141
	2- 4	99	512	1034	-
	4- 6	79	323	787	-
	6-10	22	189	297	-
	10-15	4	23	132	-

Table D 4

Total suspended matter (TSM) (μg/kg)

(after removal of seasalt)

Cruise, station and date	Depth (m)	TSM	Cruise, station and date	Depth (m)	TSM
Cruise B[1]					
S 26	0	2000	S 29	0	2200
August 1971	2	3300	August 1971	5	3200
	5	2400		10	1700
	10	1300		20	900
	20	900		50	800
	30	900			
	40	1200	S 32	0	2300
			August 1971	10	1900
				30	1000
				40	800
Cruise I[2]					
S 41	0	3300	H 35	0	3200
August 1973	5	1000	August 1972	5	1100
	10	1900		10	800
	25	900		100	600
	50	900		350	400
	75	700		400	600
	100	800		550	700
	125	900		600	1900
	175	400		650	600
	200	600		700	900
	250	600			
	275	400			
Cruise II[2]					
S 59	75	70	S 58	0	500
September 1973	100	70	September 1973	10	70
	150	60		20	120
	200	80		70	60
	250	80		90	50
	310	85		125	60
	330	80		150	55
	350	115		200	45
	385	115		225	90
				250	60

Table D 4 continued

Cruise, station and date	Depth (m)	TSM	Cruise, station and date	Depth (m)	TSM
Cruise III[2]					
H 68	0	140	H 70	5	190
April 1974	10	100	April 1974	25	425
	25	890		50	125
	50	70		100	70
	100	60		300	170
	150	30		400	40
	200	85		500	50
	350	15		550	35
	550	40		600	40
				700	170
				825	110

1 Sartorius 0.45μ membrane filters

2 Nuclepore 0.4μ membrane filters

Table D 5

Suspended particulate matter and dissolved metal data

Cruise, station and date	Depth (m)	Suspended particulate matter (µg/kg)													Dissolved metals (µg/kg)				
		Ca	K	Fe	Ti	Si	Al	Mg	P	Mn	S	Cu	Pb	Zn	Fe	Mn	Cu	Pb	Zn
Cruise B[1]																			
S 26	0	9.51	36.50	107.00	4.57	235.80	118.70	25.74	10.53	1.35	14.84	1.02	8.92	16.57					2540
Aug 1971	2	17.05	24.07	47.40	1.97	116.40	49.50	17.08	28.24	2.10	36.20	0.37	3.59	11.12					2240
	5	21.60	12.30	47.40	0.93	54.00	16.30	6.58	22.97	-	-	-	-	-					320
	10	48.20	8.01	79.90	0.82	53.50	19.71	3.12	9.04	2.45	19.09	-	-	-					670
	20	69.50	3.60	17.84	0.31	21.77	8.21	2.23	5.89	1.30	6.19	-	-	-					330
	30	47.60	2.35	32.20	0.33	20.53	7.48	1.62	11.61	0.89	9.57	0.53	16.59	11.15					1120
	40	72.70	3.12	49.90	0.55	26.27	12.82	2.55	18.22	0.69	13.43	0.52	27.92	14.64					1180
S 27	0	9.56	31.60	71.50	3.54	191.00	82.40	21.35	14.64	1.10	14.38	0.68	4.18	6.21					1680
Aug 1971	1	20.48	35.50	89.50	4.38	229.00	107.70	24.24	11.10	1.14	13.12	0.87	2.82	9.55					-
	5	41.10	11.62	48.00	0.98	57.90	24.90	6.47	24.51	13.21	28.07	1.00	14.46	41.40					290
	10	60.40	6.15	32.90	0.59	40.50	13.91	3.32	9.24	3.07	12.87	0.60	13.72	17.85					340
	20	103.80	3.89	31.70	0.42	28.89	11.88	6.92	13.00	2.37	18.67	1.89	11.14	36.30					390
	30	175.60	2.38	33.20	0.42	24.20	10.04	2.65	13.83	1.18	10.21	0.26	14.38	17.80					1125
S 28	0	7.59	38.90	120.30	4.49	245.80	146.40	25.20	10.98	1.35	17.38	1.32	14.14	25.68					4595
Aug 1971	5	30.09	16.42	89.50	1.18	68.30	29.82	10.16	33.00	15.74	38.50	1.57	22.93	51.20					280
	10	51.40	12.28	87.60	1.11	69.80	29.10	6.67	18.91	8.58	30.30	2.04	32.00	-					445
	15	32.80	8.42	80.10	0.89	59.60	25.87	4.53	11.87	5.13	29.57	1.45	36.90	35.90					430
	20	48.50	6.94	86.20	0.62	43.60	16.79	3.38	7.41	2.39	37.10	1.14	42.60	30.80					360
S 29	0	12.44	31.10	71.40	3.50	182.90	88.10	21.83	14.03	1.83	14.16	0.25	4.79	8.66					1250
Aug 1971	5	32.30	11.80	27.26	0.71	49.70	18.89	8.52	29.65	8.07	32.20	0.76	3.11	-					170
	10	53.00	9.48	30.60	0.90	56.90	22.31	6.49	10.81	4.46	13.48	0.66	9.99	14.02					160
	20	56.70	4.54	17.31	0.43	26.19	10.64	3.01	4.63	2.33	8.60	0.14	6.06	7.32					83
	50	12.99	2.38	30.20	0.25	18.03	5.82	1.36	7.54	0.42	11.33	0.41	14.93	9.23					690
S 30	0	10.57	21.58	52.50	2.49	134.00	63.40	13.71	12.25	2.66	20.76	0.84	7.33	10.79					820
Aug 1971	5	21.97	9.72	25.62	0.94	65.80	18.76	5.63	18.66	4.00	22.54	0.58	2.99	-					120
	10	29.11	6.12	16.44	0.64	41.90	13.47	3.96	6.35	2.46	7.59	0.10	3.16	5.19					95
	30	63.00	3.41	5.93	0.28	21.91	5.49	1.95	4.64	1.34	4.38	n. d.	1.21	3.61					130
	80	2.94	2.78	10.07	0.25	14.15	4.20	1.44	3.51	1.07	3.82	0.15	3.55	2.85					280
	150	2.78	2.46	23.90	0.19	14.00	4.12	1.09	4.21	3.09	2.65	n. d.	4.39	1.67					< 50

Table D 5 continued

Cruise, station and date	Depth (m)	Suspended particulate matter (µg/kg) Ca	K	Fe	Ti	Si	Al	Mg	P	Mn	S	Cu	Pb	Zn	Dissolved metals (µg/kg) Fe	Mn	Cu	Pb	Zn
Cruise B[1] (continued)																			
S 31	0	21.49	14.84	26.95	1.08	61.80	30.50	11.75	20.37	9.24	43.60	0.51	3.08	22.77					1060
Aug 1971	5	47.80	14.32	43.26	0.83	48.20	18.19	8.88	31.60	14.13	41.50	0.61	9.74	-					215
	10	65.70	11.63	52.90	1.24	71.20	26.27	6.61	10.18	5.48	20.34	0.47	18.40	21.26					300
	20	75.00	7.41	144.50	0.69	41.50	14.19	3.45	4.63	2.22	47.90	1.57	58.00	34.80					590
S 32	0	15.41	26.61	55.10	2.68	166.20	54.50	17.75	13.54	2.51	19.44	0.11	6.32	20.34					-
Aug 1971	10	32.50	7.11	13.70	0.70	43.10	9.65	4.55	6.26	1.61	12.39	n. d.	0.70	3.66					<50
	30	66.90	2.98	4.30	0.22	21.75	3.63	2.84	3.27	1.42	5.64	-	-	-					69
	80	8.35	1.07	4.54	0.15	14.81	2.83	1.09	1.19	1.85	2.06	n. d.	2.23	1.32					81
S 33	0	10.28	13.83	30.50	1.49	163.70	31.80	9.16	6.91	1.40	17.07	0.13	3.65	-					200
Aug 1971	10	47.40	3.83	4.41	0.26	22.14	4.25	2.88	3.82	0.89	10.42	n. d.	n. d.	2.07					<50
	30	47.20	3.19	2.59	0.12	15.40	2.86	2.13	1.78	0.87	5.24	n. d.	n. d.	1.41					<50
Cruise I[2]																			
S 34	0	13.23	25.61	60.70	3.00	179.10	62.00	18.84	12.13	0.74	53.00	n. d.	0.51	10.35					240
Aug 1972	5	4.69	1.96	6.51	0.28	20.04	3.94	1.51	5.00	1.38	27.32	1.54	n. d.	21.51					-
	10	0.71	1.35	2.97	0.10	11.83	1.83	0.76	2.01	0.83	6.10	0.57	n. d.	0.28					175
	15	0.80	1.67	2.82	0.11	9.59	1.78	0.96	3.00	1.46	7.93	2.21	n. d.	0.30					<50
	20	5.28	1.54	2.91	0.18	17.20	3.24	2.30	2.63	1.45	6.80	1.06	n. d.	0.85					167
	30	1.21	1.19	3.27	0.16	12.56	2.37	1.08	1.95	1.27	4.73	0.60	0.18	0.27					71
	40	1.19	1.54	3.40	0.18	18.88	3.58	1.20	1.29	1.45	3.68	0.89	1.56	0.10					50
	50	0.77	0.66	2.26	0.11	9.41	1.74	0.56	0.98	1.61	2.34	0.63	1.94	0.18					70
	75	0.69	1.07	3.69	0.16	13.67	2.86	0.83	1.09	1.67	2.69	0.24	2.39	0.18					73
	100	0.64	0.99	7.15	0.18	16.63	3.88	1.39	1.23	1.82	3.02	n. d.	1.08	0.29					69
	125	0.84	1.26	8.17	0.19	14.30	3.28	1.02	1.65	1.55	2.72	n. d.	n. d.	0.21					
	150	0.58	0.93	6.46	0.13	10.14	2.50	0.82	1.06	1.06	2.12	0.62	n. d.	0.13					
	200	0.51	1.36	5.16	0.18	10.51	3.30	1.05	0.72	1.04	1.29	0.21	n. d.	0.12					
	225	1.14	3.23	10.79	0.42	22.21	7.86	2.83	0.83	1.73	2.13	0.59	n. d.	0.25					
	250	1.16	3.91	8.70	0.40	16.61	6.63	2.54	1.04	1.89	1.91	0.65	n. d.	0.15					
	275	1.06	2.69	7.85	0.31	18.82	6.85	2.12	0.72	1.98	1.70	0.67	n. d.	0.20					

Table D 5 continued

Cruise, station and date	Depth (m)	Suspended particulate matter (µg/kg) Ca	K	Fe	Ti	Si	Al	Mg	P	Mn	S	Cu	Pb	Zn	Dissolved metals (µg/kg) Fe	Mn	Cu	Pb	Zn
Cruise I[2]	(continued)																		
S 36	0	5.97	24.89	53.10	2.94	151.30	61.40	19.11	5.25	1.16	16.35	1.45	2.43	2.37	16.1	21.6			164+
Aug 1972	5	1.76	2.44	5.39	0.31	20.46	5.34	1.63	2.60	0.79	6.16	0.52	n. d.	1.14	2.0	2.0			126+
	10	3.46	4.09	10.45	0.36	35.93	6.99	2.08	6.62	1.84	15.06	1.48	1.35	0.72	3.4	2.2			71+
	15	1.27	1.76	5.10	0.32	18.47	4.13	1.24	4.42	1.16	9.40	1.13	1.89	0.32	1.6	0.6			135+
	25	0.42	0.95	3.06	0.12	12.11	2.38	0.89	2.20	1.68	4.94	0.57	1.44	0.23	8.6	2.3			197+
	50	0.69	0.92	5.39	0.17	14.13	2.76	0.84	1.35	2.31	3.19	0.59	4.83	0.24	5.4	0.4			96+
	75	0.71	1.26	4.64	0.19	15.50	3.38	1.01	1.28	1.68	2.70	0.30	3.72	0.16	1.4	1.1			64+
	100	0.32	1.00	4.88	0.14	13.48	2.89	0.96	1.23	1.20	2.07	0.40	1.24	0.45	0.6	0.5			49+
	125	3.42	1.93	10.67	0.45	24.43	8.18	2.64	1.48	1.39	2.29	0.76	1.54	0.19	2.3	0.3			64+
	150	0.51	1.08	8.13	0.18	10.92	3.11	0.89	1.13	1.22	1.84	0.48	0.50	0.13	2.4	0.4			29+
	200	0.56	1.04	4.41	0.14	7.36	2.62	0.89	0.85	0.91	1.29	0.47	n. d.	n. d.	-	-			-
	250	0.26	1.37	4.92	0.14	10.02	3.48	1.42	0.80	1.14	1.57	1.06	n. d.	n. d.	-	-			-
	300	1.18	3.02	12.50	0.38	21.53	7.94	2.78	0.74	2.64	2.09	1.12	1.32	0.14	1.7	0.8			10.5+
	325	1.13	3.42	10.06	0.40	21.59	8.06	2.60	0.84	2.45	1.91	0.46	0.99	0.17	-	-			-
	350	1.48	4.16	14.58	0.51	27.56	9.58	3.24	1.02	2.56	2.19	0.93	n. d.	n. d.	-	-			-
	375	1.44	3.92	12.26	0.46	25.54	9.48	3.69	1.31	2.84	3.75	1.01	0.49	0.18	2.1	1.5			13.4+
S 37	0	11.10	30.43	65.70	3.54	191.70	73.60	24.85	9.04	1.49	29.60	3.25	n. d.	3.50					99
Aug 1972	5	4.30	8.04	23.81	1.05	59.96	19.14	6.65	5.85	0.87	14.53	2.52	n. d.	0.79					80
	10	1.89	3.64	8.35	0.49	37.56	8.95	3.00	5.26	1.17	11.40	1.46	1.82	0.61					71
	50	0.54	1.12	3.51	0.15	16.41	3.03	1.01	1.45	2.57	3.42	0.66	5.50	0.33					90
S 38	0	12.33	40.15	88.30	4.76	267.10	97.80	30.60	11.13	1.55	33.50	5.45	0.63	4.14					162
Aug 1972	5	2.33	4.11	17.40	0.60	33.60	9.93	3.36	6.29	0.91	13.62	2.63	n. d.	0.97					84
	10	1.65	2.62	10.46	0.34	26.38	5.88	1.66	4.74	0.94	11.89	1.51	n. d.	0.60					91
	50	0.70	0.95	3.37	0.18	13.59	2.70	0.82	1.22	2.48	2.90	n. d.	3.80	0.35					98
S 39	0	9.54	32.90	72.30	3.93	189.10	79.20	24.11	6.13	1.55	13.63	2.13	n. d.	3.06					176
Aug 1972	5	2.74	5.41	16.47	0.72	37.80	12.49	4.17	5.86	0.91	11.61	0.89	2.75	0.59					78
	10	1.50	1.69	4.52	0.21	15.72	3.65	1.30	3.48	0.94	9.44	0.41	1.96	0.30					86
	50	0.25	0.86	3.26	0.13	14.26	2.47	0.77	1.30	2.48	3.19	0.37	4.15	0.31					95
S 40	0	5.97	19.00	42.70	2.23	104.20	43.70	13.07	2.98	0.58	7.40	3.55	n. d.	1.28					189
Aug 1972	5	4.35	4.76	10.86	0.61	44.50	10.50	3.24	6.01	1.29	10.90	1.32	n. d.	1.06					63
	10	0.50	1.40	3.31	0.18	15.30	3.22	1.14	3.13	0.88	7.93	0.83	n. d.	0.33					< 50
	50	0.53	0.93	4.24	0.17	13.46	2.50	0.68	1.15	1.91	2.52	0.52	4.82	0.19					84

Table D 5 continued

Cruise, station and date	Depth (m)	Suspended particulate matter (µg/kg) Ca	K	Fe	Ti	Si	Al	Mg	P	Mn	S	Cu	Pb	Zn	Dissolved metals (µg/kg) Fe	Mn	Cu	Pb	Zn
Cruise I[2]	(continued)																		
S 41	0	14.34	36.20	67.70	3.74	177.00	76.90	25.44	10.21	2.42	14.85	4.40	8.01	6.61	-	-	-	-	-
Aug 1972	5	11.70	29.35	66.40	3.39	156.90	66.70	21.41	8.74	2.83	14.20	2.08	2.95	4.30	-	-	-	-	-
	10	2.18	2.50	5.12	0.31	16.35	5.29	1.85	2.16	0.59	4.14	1.27	0.13	0.48	32.2	5.0	6.3	11.3	132+
	15	2.94	3.46	12.90	0.51	33.78	8.13	2.87	6.46	2.46	13.53	1.80	n. d.	1.02	12.3	10.5	3.9	22.7	138+
	25	1.73	2.14	8.64	0.32	17.73	4.71	1.68	3.31	1.44	7.69	1.35	2.24	0.80	5.7	22.0	1.9	39.5	356+
	50	0.37	0.90	3.32	0.14	11.00	2.31	0.60	1.16	3.28	3.28	0.84	6.79	0.29	2.7	2.8	2.3	16.7	194+
	75	0.70	0.91	6.07	0.14	9.76	2.30	0.63	1.97	-	-	0.45	4.87	0.39	3.6	8.0	2.0	22.3	168+
	100	0.71	0.93	8.11	0.16	11.23	2.53	0.69	1.96	2.20	3.03	0.55	4.36	0.38	3.5	1.6	2.0	9.0	110+
	125	1.53	1.12	12.45	0.26	11.00	3.27	0.91	2.47	2.45	3.07	0.29	2.28	0.46	2.6	0.5	1.2	2.8	98+
	150	0.86	1.34	17.15	0.22	11.96	3.50	1.08	2.63	-	-	0.66	3.72	0.39	4.1	0.6	1.2	4.9	63+
	175	0.34	1.16	15.14	0.16	9.56	3.09	0.95	2.34	-	-	0.54	1.74	0.31	2.2	0.7	0.8	2.2	50+
	200	0.51	1.82	13.05	0.24	14.89	4.69	1.61	1.81	2.33	2.47	0.70	2.80	0.19	3.0	0.6	1.4	4.2	65+
	225	1.64	4.99	17.41	0.62	33.80	12.06	4.01	1.44	3.96	2.73	0.44	2.05	0.44	2.2	0.6	0.8	2.3	21+
	250	1.10	4.39	14.11	0.51	30.30	10.34	3.71	1.29	4.28	2.11	0.44	0.29	0.37	1.4	0.9	1.1	1.4	11.5+
	275	1.41	5.25	18.44	0.63	37.00	12.94	4.97	1.29	5.32	2.14	0.64	n. d.	0.37	2.0	0.7	0.6	9.5	9.0+
S 42	0	11.19	29.74	72.70	3.61	166.80	70.60	22.50	8.50	1.69	15.96	0.70	6.57	3.77					-
Aug 1972	5	5.30	19.00	63.70	2.13	110.30	46.10	14.69	5.37	1.88	10.52	1.83	n. d.	1.95					156
	10	3.57	3.60	8.70	0.47	35.40	7.91	2.60	7.60	1.54	15.11	1.65	2.08	0.98					76
	50	1.29	2.04	7.11	0.33	17.80	5.66	1.97	1.87	2.12	3.58	0.66	10.04	0.39					-
S 43	0	11.91	31.50	75.30	3.60	176.10	74.20	22.46	8.33	2.71	16.49	1.94	n. d.	4.19					-
Aug 1972	5	7.19	22.24	53.70	2.57	132.10	53.60	16.89	6.72	2.00	14.12	1.46	3.17	2.78					-
	10	5.23	2.11	4.65	0.24	23.99	4.56	2.26	5.78	1.09	11.18	1.23	n. d.	0.89					59
	50	0.91	0.78	5.58	0.13	10.73	3.00	0.71	1.48	2.82	2.80	0.80	6.84	0.30					-
S 45	0	11.22	34.90	69.30	3.83	174.90	77.70	26.19	7.40	2.21	16.86	1.02	9.35	2.60	63.0	15.4	6.3	29.0	125+
Aug 1972	10	4.96	14.41	36.80	1.69	99.70	33.90	11.05	5.82	2.89	12.35	2.79	n. d.	1.61	73.9	16.5	7.0	15.1	113+
	25	1.47	2.54	7.96	0.26	19.91	6.13	1.76	3.76	1.09	8.87	1.80	5.59	0.90	62.2	39.9	7.7	80.0	607+
	50	1.51	1.34	17.20	0.25	16.86	4.54	0.91	4.69	1.37	8.10	1.12	6.90	1.33	29.3	25.2	5.7	34.5	492+
	75	0.98	0.99	19.80	0.19	12.51	3.91	0.81	4.96	1.32	7.75	0.62	7.03	1.23	15.6	11.0	3.2	31.7	242+
	100	0.65	0.95	17.58	0.15	10.57	2.61	0.71	1.94	1.99	2.76	0.47	3.72	0.36	7.0	2.9	4.1	8.8	110+
	150	0.45	0.82	19.32	0.12	8.15	2.51	0.71	3.22	2.24	2.39	0.85	3.33	0.42	9.2	2.2	2.3	8.5	29+
	225	1.59	4.03	20.29	0.47	26.72	9.65	3.87	2.16	4.51	4.03	0.54	0.82	0.52	2.8	2.8	1.8	4.2	13.5+

Table D 5 continued

Cruise, station and date	Depth (m)	Suspended particulate matter (µg/kg) Ca	K	Fe	Ti	Si	Al	Mg	P	Mn	S	Cu	Pb	Zn	Dissolved metals (µg/kg) Fe	Mn	Cu	Pb	Zn
Cruise I[2] (continued)																			
S 46	0	21.25	92.00	177.00	9.87	452.20	204.60	63.80	14.21	2.54	17.70	4.37	5.92	4.56	105.0	28.6	9.5	52.5	124
Aug 1972	5	10.04	35.30	77.40	4.00	179.60	80.40	24.54	7.47	1.38	10.39	1.84	n. d.	2.78	263.0	20.5	33.0	22.0	155
	10	12.00	20.71	41.70	2.38	114.80	46.00	13.94	6.50	1.54	12.35	2.30	0.68	2.91	56.4	15.5	92.0	20.0	117
	15	3.96	7.84	16.91	0.80	48.40	17.14	5.60	8.17	2.25	16.00	2.14	1.43	1.92	-	-	-	-	-
	25	3.30	2.22	17.49	0.32	24.20	7.18	2.03	6.43	1.11	14.66	2.87	4.48	2.70	58.0	44.0	5.6	65.2	1090
	50	2.42	1.10	32.50	0.30	22.41	6.37	0.90	9.96	0.61	13.84	0.42	9.66	2.46	6.8	29.2	4.8	76.7	724
	75	1.38	0.70	22.14	0.19	8.69	3.75	0.50	6.61	0.68	7.79	0.40	9.09	1.14	6.8	12.8	1.8	30.2	239
	100	0.62	0.69	42.40	0.15	9.38	2.21	0.56	3.18	1.26	3.76	0.52	2.58	0.57	2.7	4.3	2.0	11.3	104
River Ullensvang		231.80	135.90	677.20	36.50	1182.90	489.80	190.00	9.24	10.02	12.08	-	3.10	1.90	42.5	2.4	4.5	-	25.7+
River Espe		4.70	3.16	11.26	0.73	24.85	11.81	3.80	1.51	0.20	5.96	-	0.10	<0.10	-	-	-	-	-
River Fossa		26.53	51.70	173.70	12.34	358.30	152.50	61.70	3.80	1.86	5.16	-	0.30	0.40	-	-	-	-	-
Lake Ringdalsvann		2.23	11.77	24.75	1.68	66.50	40.40	6.29	1.45	1.14	6.21	-	0.40	0.30	5.2	5.6	2.2	-	15.3+
Lake Sandvevann		60.10	231.50	602.00	32.60	1052.20	472.20	122.40	7.73	4.82	9.13	-	-	-	-	-	-	-	-
River Opo (upper)		66.60	273.20	628.10	39.40	1137.60	517.00	127.80	8.69	6.76	9.84	-	3.20	1.80	32.5	7.1	3.4	-	15.0+
River Opo (lower)		63.70	251.90	550.80	34.50	1073.20	480.40	121.20	8.03	5.14	8.80	-	-	-	-	-	-	-	-
Cruise II[2]																			
S 58	0	9.08	8.51	18.80	0.79	39.70	24.41	9.06	13.20	2.77	10.56	-	5.8	3.2					221
Sep 1973	5	7.55	3.18	8.18	0.24	19.58	6.49	3.64	4.64	1.44	5.53	-	3.8	0.7					51
	10	3.16	0.98	2.23	0.11	6.32	2.21	1.39	1.55	0.57	2.78	-	1.0	0.2					50
	20	7.03	1.56	3.80	0.23	12.51	4.12	1.98	1.82	0.89	3.32	-	-	-					59
	25	3.37	0.94	2.02	0.11	7.03	1.96	1.00	1.35	0.48	1.72	-	1.1	0.2					<50
	30	2.54	0.34	0.86	0.05	3.35	0.75	0.50	0.77	0.39	1.53	-	0.6	0.1					<50
	50	1.41	0.11	0.36	0.02	1.40	0.39	0.14	0.27	0.22	0.46	-	<0.1	<0.1					64
	70	3.26	0.38	1.03	0.05	2.85	0.91	0.47	0.59	0.52	0.95	-	0.4	0.2					64
	80	2.69	0.39	1.02	0.05	3.30	1.01	0.31	0.34	0.28	0.71	-	0.3	0.1					80
	90	4.62	0.63	1.97	0.08	5.19	1.92	0.74	0.67	0.55	0.97	-	0.7	0.2					78
	100	5.73	0.64	1.85	0.09	5.99	1.67	0.85	0.70	0.66	1.15	-	0.4	0.2					55
	125	5.40	0.95	2.80	0.10	6.65	2.11	1.56	0.69	0.63	1.36	-	0.4	0.2					55
	150	5.45	0.91	4.00	0.11	7.87	2.48	1.10	0.90	0.92	1.03	-	1.3	0.3					<50
	200	4.75	1.50	4.41	0.17	10.12	4.02	1.53	0.68	1.02	1.03	-	0.6	0.2					<50
	225	5.69	2.46	6.34	0.28	15.59	6.10	2.30	0.78	1.36	1.50	-	0.9	0.2					<50
	250	4.30	1.54	3.88	0.14	9.32	3.63	1.51	0.61	1.26	1.48	-	0.9	0.3					

Table D 5 continued

Cruise, station and date	Depth (m)	Suspended particulate matter (µg/kg) Ca	K	Fe	Ti	Si	Al	Mg	P	Mn	S	Cu	Pb	Zn	Dissolved metals (µg/kg) Fe	Mn	Cu	Pb	Zn
Cruise II[2]	(continued)																		
S 59	0	12.80	13.98	27.81	1.30	65.80	42.40	9.29	16.84	1.75	9.19	-	2.5	2.9	6.5	40.3	4.7	-	474+
Sep 1973	3	9.34	4.22	7.84	0.42	24.41	9.21	4.54	6.09	3.10	7.41	-	0.6	1.0	5.8	1.9	2.2	-	34.2+
	8	3.69	2.00	5.27	0.30	15.49	4.78	2.35	2.86	1.00	4.31	-	0.1	0.4	-	-	-	-	-
	22	0.76	0.30	0.62	0.03	2.12	0.66	0.29	0.41	0.28	0.67	-	<0.1	0.1	1.8	1.9	1.6	-	25.4+
	50	4.95	0.35	1.70	0.08	3.95	1.60	0.86	1.37	1.20	1.89	-	2.1	0.3	3.6	39.8	2.8	13.3	319+
	75	5.80	0.88	2.97	0.12	7.99	2.46	1.16	1.35	1.21	1.89	-	2.0	0.3	3.3	12.7	2.4	2.3	182+
	100	5.17	0.97	3.02	0.12	7.96	2.75	1.22	1.01	1.62	1.32	-	1.8	0.3	2.0	1.1	1.6	-	87+
	150	3.95	0.39	4.39	0.07	3.55	1.67	0.66	1.17	1.26	1.11	-	1.0	0.3	-	-	-	-	-
	200	3.06	0.92	2.97	0.09	4.43	1.81	1.21	0.62	0.91	1.38	-	0.4	0.1	2.1	0.3	3.0	-	23.9+
	250	4.84	2.28	8.44	0.23	13.96	5.87	3.39	1.18	4.11	1.48	-	-	0.4	-	-	-	-	-
	300	5.89	3.09	8.90	0.42	22.33	8.50	2.84	0.84	4.95	1.16	-	0.5	0.4	-	-	-	-	-
	310	4.85	0.57	2.15	0.09	5.16	1.68	0.98	1.22	1.67	1.52	-	2.2	0.3	-	-	-	-	-
	330	2.77	2.07	5.88	0.27	14.59	5.80	1.69	0.57	3.99	1.00	-	0.3	0.3	-	-	-	-	-
	350	5.33	2.85	7.93	0.33	20.18	8.26	2.50	0.81	5.72	1.09	-	0.9	0.5	-	-	-	-	-
	385	6.27	3.36	7.96	0.33	21.94	8.78	4.01	0.76	8.19	1.12	-	0.3	0.8	0.8	0.3	0.9	-	10.9+
S 63	0	29.20	13.68	26.72	0.97	59.20	39.00	12.63	24.79	2.55	16.56	-	4.2	3.4					436
Sep 1973	5	10.31	4.07	11.69	0.53	25.16	9.59	6.01	7.76	3.06	9.25	-	0.6	0.8					65
	10	3.53	2.82	6.94	0.30	18.31	5.77	4.21	4.67	1.89	5.88	-	1.7	0.5					<50
	20	6.45	2.13	5.75	0.14	14.92	4.82	3.45	4.25	3.42	5.02	-	1.1	1.0					58
	30	10.39	2.21	14.03	0.35	23.94	9.72	4.39	11.26	6.13	5.37	-	5.2	3.1					667
	40	16.74	2.22	34.80	0.52	39.30	10.88	5.03	18.96	2.21	13.08	-	11.7	4.4					1146
	50	61.50	1.86	46.20	0.87	48.20	17.46	5.01	25.49	0.99	29.04	-	17.1	7.0					1437
	60	52.40	1.46	38.30	0.64	35.20	14.10	2.74	17.59	0.93	27.27	-	12.8	5.5					1000
	70	91.60	2.45	55.50	1.36	41.10	28.86	6.28	38.40	0.69	40.20	-	19.5	8.3					998
	80	62.00	1.88	42.80	1.01	25.69	22.19	4.45	29.95	0.52	27.35	-	15.5	5.6					746
	90	34.00	1.01	27.39	0.58	15.28	12.27	2.78	16.40	0.45	15.99	-	9.7	3.2					517
	100	15.62	0.73	18.27	0.31	9.63	5.87	1.86	8.36	0.35	9.21	-	5.7	1.8					347
	110	8.66	0.72	15.99	0.18	8.30	3.36	1.62	4.83	0.46	6.97	-	4.2	1.3					226
	120	11.99	1.37	23.76	0.29	14.15	4.95	2.44	6.04	1.14	8.12	-	6.4	1.7					144
	130	9.73	0.99	24.70	0.16	10.89	3.59	2.32	6.36	1.28	5.51	-	5.9	1.7					103

Table D 5 continued

Cruise, station and date	Depth (m)	Suspended particulate matter (µg/kg) Ca	K	Fe	Ti	Si	Al	Mg	Dissolved metals (µg/kg) P	Mn	S	Cu	Pb	Zn	Fe	Mn	Cu	Pb	Zn
Cruise II[2]	(continued)																		
S 64	0	35.40	21.59	60.80	1.42	95.90	47.60	14.33	75.70	1.67	30.60	-	15.4	13.5					1371
Sep 1973	5	22.48	5.49	17.01	0.53	40.80	15.42	4.11	19.74	3.79	11.71	-	2.6	3.9					656
	10	18.94	2.50	12.85	0.37	25.03	11.73	1.39	11.32	5.11	6.78	-	2.7	3.6					346
	20	109.50	3.39	17.63	0.50	28.43	13.09	6.37	15.90	5.63	12.53	-	3.6	4.5					577
	30	45.60	3.32	35.50	0.64	32.80	21.51	7.55	35.40	2.80	9.03	-	8.8	5.6					1552
	40	95.30	4.66	91.80	2.05	76.70	33.80	6.85	64.40	1.25	40.70	-	26.9	11.9					2697
Cruise III[2]																			
S 69	0	5.00	0.57	6.48	0.17	17.56	2.05	0.34	4.26*	0.45*	1.83	-	1.3*	0.7*					154
Apr 1974	5	3.46	0.62	3.08	0.18	18.33	2.73	0.39	4.79	0.66	3.31	-	1.7	0.8					117
	10	-	-	2.09	0.07	16.82	2.00	-	5.57	1.09	-	-	1.2	0.8					80
	25	0.56	0.36	1.06	0.06	46.45	1.78	0.19	4.98	3.12	1.99	-	2.1	1.4					120
	50	2.19	1.10	4.04	0.11	58.28	3.10	0.81	3.85	2.09	1.30	-	3.5	0.8					154
	100	1.66	0.58	3.34	0.15	13.84	1.18	0.34	1.34	0.91	0.95	-	0.7	0.3					97
	200	-	-	2.85	0.15	12.86	2.22	-	0.88	0.57	-	-	0.4	0.2					51
	250	2.77	1.84	5.78	0.23	37.30	4.29	1.51	1.66	1.21	0.85	-	0.6	0.3					-
	300	2.61	2.44	8.92	0.28	25.48	5.49	1.98	1.46	2.60	0.94	-	0.9	0.4					-
	325	-	-	8.88	0.22	17.45	5.02	-	1.06	3.20	-	-	0.4	0.2					-
	340	1.77	2.58	9.51	0.24	24.48	5.91	2.47	1.28	3.70	0.68	-	0.6	0.3					-
S 71	0	8.06	3.71	43.30	0.87	111.10	20.34	2.57	33.90	0.38	5.86	-	9.7	7.9					500
Apr 1974	5	3.54	0.86	5.60	0.17	21.39	4.34	0.45	7.23	0.55	3.62	-	1.4	1.1					109
	10	6.61	0.58	1.85	0.13	67.50	2.26	0.60	5.92	1.35	4.23	-	1.3	0.9					77
	25	5.54	0.84	3.26	0.16	70.10	3.79	1.32	8.57	3.66	7.05	-	3.0	2.2					120
	50	5.62	1.01	7.50	0.21	77.80	4.20	0.92	6.82	1.52	2.00	-	5.5	1.6					266
	100	2.83	1.36	8.40	0.19	26.28	3.90	0.87	2.45	1.69	1.17	-	2.4	0.6					69
	150	3.52	1.81	6.89	0.23	24.84	4.48	1.72	1.77	1.23	1.02	-	1.4	0.3					-
	200	3.03	3.17	11.65	0.35	34.70	7.49	2.74	1.87	1.94	0.89	-	1.4	0.5					54
	250	3.55	3.14	14.08	0.34	30.90	7.46	2.70	1.85	4.13	0.78	-	1.0	0.5					-
	300	3.23	3.46	12.25	0.38	26.24	8.22	3.16	1.39	4.47	0.66	-	0.6	0.5					-
	350	4.62	5.43	16.34	0.51	42.40	12.11	5.15	1.82	8.46	0.81	-	1.3	0.8					-
	375	5.95	8.50	24.39	0.81	62.50	19.58	8.00	2.18	12.00	0.82	-	1.1	0.8					<50

Table D 5 continued

Cruise, station and date	Depth (m)	Suspended particulate matter (µg/kg) Ca	K	Fe	Ti	Si	Al	Mg	Dissolved metals (µg/kg) P	Mn	S	Cu	Pb	Zn	Fe	Mn	Cu	Pb	Zn
Cruise III[2]	(continued)																		
S 72	0	18.74	10.89	148.70	3.48	108.70	87.40	7.34	80.00	0.86	7.48	-	28.5	12.9					1050
Apr 1974	5	13.96	1.27	27.83	0.31	66.10	9.56	1.56	19.39	0.74	6.82	-	5.0	5.5					469
	10	9.52	0.62	9.73	0.15	49.10	4.47	1.02	13.13	0.74	9.81	-	2.2	2.2					-
	25	5.34	0.99	5.95	0.12	80.40	3.94	0.41	10.66	2.49	6.48	-	6.7	3.0					371
	50	16.82	1.21	22.16	0.40	62.20	6.49	0.52	12.41	1.00	6.73	-	7.8	3.0					500
	75	-	-	33.20	0.24	26.50	3.70	-	7.09	0.87	-	-	5.5	2.1					137
	100	3.39	0.82	23.69	0.14	10.53	2.80	0.52	4.96	1.43	1.37	-	3.9	1.0					57
	110	4.93	1.38	40.90	0.23	25.42	4.67	0.55	9.06	1.74	2.69	-	5.0	1.7					50
S 73	0	22.95	12.94	213.70	5.90	96.50	78.50	4.74	110.10	0.97	7.29	-	47.1	14.8					1770
Apr 1974																			

n.d. not detectable

1 Sartorius membrane filters, 0.45µ used.

2 Nucleopore membrane filters, 0.4µ used.

* All samples analysed before washing (P, Mn, Pb and Zn).

\+ Zn analysed after solvent-extraction procedure.

Table D 6

Particulate non-silicate Si, Fe and Mn (µg/kg)

Cruise, station and date	Depth (m)	non-sil Si	non-sil Fe	non-sil Mn
Cruise B				
S 26	0	0.00	44.80	0.17
Aug 1971	2	7.39	22.68	1.60
	5	18.17	39.20	-
	10	10.20	70.00	2.25
	20	3.71	13.73	1.22
	30	4.07	28.49	0.82
	40	0.00	43.50	0.56
S 27 -	0	9.63	30.30	0.28
Aug 1971	1	0.00	35.60	0.06
	5	3.16	35.60	12.96
	10	9.92	26.01	2.93
	20	2.75	25.76	2.25
	30	2.11	28.24	1.08
S 28	0	0.00	49.10	0.00
Aug 1971	5	2.76	74.60	15.44
	10	5.78	73.10	8.29
	15	2.78	67.20	-
	20	6.73	77.80	2.22
S 29	0	0.00	27.31	0.95
Aug 1971	5	8.19	17.81	7.88
	10	7.87	19.50	4.24
	20	2.78	11.99	2.22
	50	5.23	27.39	0.36
S 30	0	0.00	20.87	2.03
Aug 1971	5	24.19	16.24	3.81
	10	12.27	9.70	2.33
	30	9.83	3.18	1.29
	80	4.91	7.97	1.03
	150	4.94	21.84	3.05
S 31	0	0.00	11.67	8.93
Aug 1971	5	8.22	34.10	13.95
	10	13.41	39.80	5.22
	20	10.30	137.40	2.08
S 32	0	46.30	27.91	1.96
Aug 1971	10	21.93	8.87	1.51
	30	13.76	2.48	1.38
	80	8.58	3.12	1.82

Table D 6 continued

Cruise, station and date	Depth (m)	non-sil Si	non-sil Fe	non-sil Mn
Cruise B (continued)				
S 33	0	93.70	14.62	1.10
Aug 1971	10	12.79	2.28	0.85
	30	9.11	1.16	0.84
Cruise I				
S 34	0	42.70	29.78	0.12
Aug 1972	5	11.37	4.54	1.34
	10	7.80	2.05	0.81
	15	5.67	1.93	1.44
	20	10.07	1.29	1.42
	30	7.35	2.08	1.25
	40	10.99	1.61	1.41
	50	5.58	1.39	1.59
	75	7.38	2.26	1.64
	100	8.09	5.21	1.78
	125	7.08	6.53	1.52
	150	4.64	5.21	1.03
	200	3.25	3.51	1.01
	225	4.92	6.86	1.65
	250	2.02	5.38	1.82
	275	3.75	4.43	1.91
S 36	0	16.20	22.48	0.55
Aug 1972	5	8.71	2.72	0.74
	10	20.55	6.95	1.77
	15	9.38	3.03	1.12
	25	6.87	1.87	1.66
	50	8.06	4.01	2.28
	75	8.13	2.96	1.65
	100	7.12	3.43	1.17
	125	6.43	6.58	1.31
	150	4.08	6.57	1.19
	200	1.60	3.10	0.88
	250	2.36	3.18	1.11
	300	4.06	8.53	2.56
	325	3.86	6.03	2.37
	350	6.48	9.79	2.46
	375	4.68	7.52	2.75
S 37	0	29.63	29.81	0.75
Aug 1972	5	17.85	14.24	0.68
	10	17.87	3.87	1.08
	50	9.74	1.99	2.54
S 38	0	51.90	39.40	0.57
Aug 1972	5	11.82	12.43	0.90
	10	13.44	7.52	0.88
	50	7.65	1.82	2.45

Table D 6 continued

Cruise, station and date	Depth (m)	non-sil Si	non-sil Fe	non-sil Mn
Cruise I (continued)				
S 39	0	14.87	32.70	0.76
Aug 1972	5	10.37	10.22	0.79
	10	7.69	2.69	0.90
	50	8.83	2.02	2.46
S 40	0	8.01	20.92	0.14
Aug 1972	5	21.42	5.61	1.18
	10	8.22	1.70	0.85
	50	8.41	2.99	1.88
S 41	0	7.75	29.23	1.65
Aug 1972	5	9.97	33.00	2.16
	10	4.71	2.47	0.54
	15	15.89	8.83	2.38
	25	7.37	6.28	1.39
	50	5.92	2.16	3.26
	75	4.72	4.92	-
	100	5.66	6.84	2.17
	125	3.81	10.81	2.42
	150	4.26	15.40	-
	175	2.76	13.59	-
	200	4.50	10.70	2.28
	225	7.31	11.38	3.84
	250	7.63	8.94	4.18
	275	8.60	11.97	5.19
S 42	0	11.48	37.40	0.99
Aug 1972	5	8.84	40.70	1.42
	10	18.03	4.74	1.46
	50	5.35	4.28	2.06
S 43	0	12.53	38.20	1.97
Aug 1972	5	14.08	26.95	1.46
	10	13.96	2.37	1.04
	50	4.13	4.08	2.79
S 45	0	3.78	30.40	1.43
Aug 1972	10	25.03	19.83	2.55
	25	6.50	4.89	1.03
	50	6.87	14.93	1.32
	75	3.91	17.85	1.28
	100	4.53	16.27	1.96
	150	2.63	18.06	2.21
	225	5.50	15.46	4.41

Table D 6 continued

Cruise, station and date	Depth (m)	non-sil Si	non-sil Fe	non-sil Mn
Cruise I (continued)				
S 46	0	2.05	74.70	0.49
Aug 1972	5	2.54	37.20	0.58
	10	13.49	18.67	1.08
	15	10.77	8.34	2.08
	25	8.40	13.90	1.04
	50	8.40	29.35	0.55
	75	0.44	20.26	0.64
	100	4.52	41.30	1.24
River Ullensvang		105.10	432.20	5.12
River Espe		0.00	5.35	0.09
River Fosså		22.83	97.40	0.34
Lake Ringdalsvann		0.00	4.50	0.74
Lake Sandvevann		13.40	365.90	0.10
River Opo (upper)		15.43	369.60	1.59
River Opo (lower)		0.17	310.00	0.34
Cruise II				
S 58	0	0.00	6.59	2.53
Sep 1973	5	5.30	4.93	1.38
	10	1.46	1.12	0.55
	20	3.45	1.74	0.85
	25	2.72	1.04	0.46
	30	1.70	0.48	0.38
	50	0.54	0.16	0.22
	70	0.85	0.57	0.51
	80	1.08	0.51	0.27
	90	0.97	1.01	0.53
	100	2.32	1.01	0.64
	125	2.01	1.74	0.61
	150	2.41	2.76	0.90
	200	1.28	2.40	0.98
	225	2.17	3.29	1.30
	250	1.33	2.06	1.22
S 59	0	0.00	6.59	1.33
Sep 1973	3	4.15	3.23	3.01
	8	4.97	2.88	0.95
	22	0.67	0.29	0.27
	50	0.43	0.90	1.18
	75	2.58	1.74	1.19
	100	1.91	1.64	1.59
	150	0.00	3.55	1.24
	200	0.45	2.06	0.89
	250	1.05	5.50	4.05
	300	3.63	4.65	4.86
	310	1.46	1.31	1.65
	330	1.83	2.98	3.93
	350	2.01	3.80	5.64
	385	2.62	3.57	8.10

Table D 6 continued

Cruise, station and date	Depth (m)	non-sil Si	non-sil Fe	non-sil Mn
Cruise II (continued)				
S 63	0	0.00	7.20	2.16
Sep 1973	5	4.16	6.89	2.96
	10	5.62	4.05	1.83
	20	4.32	3.34	3.38
	30	2.56	9.17	6.03
	40	15.41	29.36	2.10
	50	9.82	37.50	0.82
	60	4.27	31.30	0.79
	70	0.00	40.70	0.40
	80	0.00	31.70	0.30
	90	0.00	21.25	0.32
	100	0.00	15.33	0.29
	110	0.91	14.31	0.43
	120	3.27	21.28	1.09
	130	2.99	22.90	1.24
S 64	0	0.00	37.00	1.19
Sep 1973	5	6.95	9.30	3.64
	10	0.00	6.98	4.99
	20	0.00	11.09	5.50
	30	0.00	24.78	2.58
	40	2.35	74.90	0.91
Cruise III				
S 69	0	13.05	5.45	0.43
Apr 1974	5	12.32	1.71	0.63
	10	12.42	1.09	1.07
	25	42.50	0.17	3.10
	50	51.40	2.49	2.09
	100	9.86	2.43	0.89
	200	7.98	1.74	0.55
	250	27.86	3.63	1.17
	300	13.40	6.17	2.55
	325	6.41	6.37	3.15
	340	11.48	6.55	3.64
S 71	0	71.40	33.21	0.18
Apr 1974	5	11.84	3.43	0.51
	10	62.60	0.72	1.32
	25	61.60	1.39	3.62
	50	68.60	5.40	1.48
	100	17.70	6.45	1.65
	150	20.30	4.65	1.19
	200	18.29	7.90	1.87
	250	14.52	10.35	4.06
	300	8.16	8.14	4.39
	350	15.76	10.28	8.34
	375	19.43	14.60	11.80

Table D 6 continued

Cruise, station and date	Depth (m)	non-sil Si	non-sil Fe	non-sil Mn
Cruise III (continued)				
S 72	0	0.00	105.00	0.00
Apr 1974	5	45.00	4.95	0.64
	10	39.30	7.50	0.70
	25	71.70	3.98	2.45
	50	47.90	18.91	0.96
	75	18.36	31.40	0.83
	100	4.37	22.29	1.40
	110	15.15	38.60	1.69
S 73	0	0.00	174.40	0.18
Apr 1974				

Table D 7

Element/Al, K/Mg and P/S ratios in particulate matter

Cruise, station and date	Depth (m)	Ca/Al	K/Al	Fe/Al	Ti/Al	Si/Al	Mg/Al	Mn/Al	K/Mg	P/S
Cruise B										
S 26	0	0.08	0.31	0.88	0.039	1.99	0.22	0.011	1.42	0.71
Aug 1971	2	0.34	0.49	0.96	0.040	2.35	0.34	0.042	1.41	0.78
	5	1.33	0.76	2.91	0.057	3.31	0.40	-	1.87	-
	10	2.45	0.41	4.06	0.042	2.72	0.16	0.124	2.57	0.47
	20	8.47	0.44	2.17	0.038	2.65	0.27	0.174	1.61	0.95
	30	6.37	0.31	4.31	0.044	2.75	0.27	0.119	1.45	1.21
	40	5.68	0.24	3.90	0.043	2.05	0.20	0.054	1.22	1.36
S 27	0	0.12	0.38	0.87	0.043	2.31	0.26	0.013	1.48	1.02
Aug 1971	1	0.19	0.33	0.83	0.041	2.13	0.23	0.011	1.47	0.85
	5	1.65	0.47	1.93	0.039	2.33	0.26	0.531	1.80	0.87
	10	4.35	0.45	2.37	0.042	2.91	0.24	0.221	1.85	0.72
	20	8.74	0.33	2.67	0.035	2.43	0.20	0.199	0.56	0.70
	30	17.50	0.24	3.31	0.042	2.41	0.26	0.118	0.90	1.35
S 28	0	0.05	0.27	0.82	0.031	1.68	0.17	0.009	1.54	0.63
Aug 1971 -	5	1.01	0.56	3.00	0.040	2.29	0.34	0.528	1.62	0.86
	10	1.77	0.43	3.01	0.038	2.40	0.23	0.295	1.84	0.62
	15	1.27	0.33	3.14	0.034	2.31	0.18	0.198	1.86	0.40
	20	2.89	0.43	5.14	0.037	2.60	0.20	0.142	2.05	0.20
S 29	0	0.14	0.35	0.81	0.040	2.07	0.25	0.021	1.43	0.99
Aug 1971	5	1.71	0.62	1.44	0.038	2.63	0.45	0.427	1.39	0.92
	10	2.38	0.42	1.37	0.040	2.55	0.29	0.200	1.46	0.80
	20	5.34	0.43	1.63	0.040	2.46	0.23	0.219	1.51	0.54
	50	2.23	0.41	5.19	0.043	3.10	0.23	0.072	1.75	0.67
S 30	0	0.17	0.34	0.83	0.039	2.12	0.22	0.042	1.57	0.59
Aug 1971	5	1.17	0.52	1.37	0.050	3.51	0.30	0.213	1.73	0.83
	10	2.16	0.45	2.21	0.048	3.11	0.29	0.183	1.55	0.84
	30	11.48	0.62	1.08	0.051	3.99	0.35	0.244	1.75	1.06
	80	0.70	0.67	2.40	0.060	3.37	0.34	0.255	1.93	0.92
	150	0.70	0.62	5.80	0.046	3.40	0.26	0.750	2.26	1.59
S 31	0	0.70	0.49	0.88	0.035	2.02	0.38	0.302	1.26	0.47
Aug 1971	5	2.63	0.79	2.38	0.046	2.65	0.49	0.777	1.61	0.76
	10	2.50	0.44	2.02	0.047	2.71	0.28	0.209	1.76	0.50
	20	5.29	0.52	10.19	0.049	2.93	0.24	0.156	2.15	0.10
S 32	0	0.28	0.49	1.01	0.049	3.05	0.33	0.046	1.50	0.70
Aug 1971	10	3.37	0.77	1.42	0.073	4.47	0.47	0.167	1.56	0.51
	30	18.45	0.89	1.18	0.061	5.99	0.78	0.391	1.05	0.58
	80	2.95	0.38	1.60	0.053	5.23	0.38	0.654	0.98	0.58
S 33	0	0.32	0.43	0.96	0.047	5.14	0.29	0.044	1.51	0.40
Aug 1971	10	11.16	0.90	1.04	0.061	5.21	0.68	0.209	1.33	0.37
	30	16.53	1.12	0.91	0.042	5.38	0.78	0.304	1.50	0.34
Cruise I										
S 34	0	0.21	0.41	0.89	0.048	2.89	0.30	0.012	1.36	0.23
Aug 1972	5	1.19	0.50	1.65	0.071	5.09	0.38	0.350	1.30	0.18
	10	0.39	0.74	1.62	0.055	6.46	0.42	0.454	1.78	0.33
	15	0.45	0.94	1.58	0.062	5.39	0.54	0.820	1.74	0.38
	20	1.63	0.48	0.90	0.056	5.30	0.71	0.448	0.67	0.39
	30	0.51	0.50	1.38	0.068	5.30	0.46	0.536	1.10	0.41
	40	0.33	0.43	0.95	0.050	5.27	0.34	0.405	1.27	0.35
	50	0.34	0.38	1.30	0.063	5.41	0.32	0.925	1.18	0.42
	75	0.24	0.37	1.29	0.056	4.78	0.29	0.584	1.29	0.41
	100	0.17	0.26	1.84	0.046	4.29	0.36	0.469	0.71	0.41
	125	0.26	0.38	2.49	0.058	4.36	0.31	0.473	1.24	0.61
	150	0.23	0.37	2.58	0.052	4.06	0.33	0.424	1.13	0.50
	200	0.16	0.41	1.56	0.055	3.19	0.32	0.315	1.30	0.56
	225	0.15	0.41	1.37	0.053	2.83	0.36	0.220	1.14	0.39
	250	0.18	0.59	1.31	0.060	2.51	0.38	0.285	1.54	0.54
	275	0.15	0.39	1.15	0.045	2.75	0.31	0.289	1.27	0.42

Table D 7 continued

Cruise, station and date	Depth (m)	Ca/Al	K/Al	Fe/Al	Ti/Al	Si/Al	Mg/Al	Mn/Al	K/Mg	P/S
Cruise I (continued)										
S 36	0	0.10	0.41	0.87	0.048	2.46	0.31	0.019	1.30	0.32
Aug 1972	5	0.33	0.46	1.01	0.058	3.83	0.31	0.148	1.50	0.42
	10	0.50	0.59	1.49	0.052	5.14	0.30	0.263	1.97	0.44
	15	0.31	0.43	1.23	0.077	4.47	0.30	0.281	1.42	0.47
	25	0.18	0.40	1.29	0.050	5.09	0.38	0.706	1.07	0.45
	50	0.25	0.33	1.95	0.062	5.12	0.30	0.837	1.10	0.42
	75	0.21	0.38	1.39	0.057	4.63	0.30	0.501	1.24	0.47
	100	0.11	0.36	1.69	0.048	4.66	0.33	0.415	1.04	0.58
	125	0.42	0.24	1.30	0.055	2.99	0.32	0.110	0.73	0.65
	150	0.16	0.35	2.61	0.058	3.52	0.29	0.392	1.21	0.61
	200	0.21	0.40	1.68	0.053	2.81	0.34	0.347	1.17	0.66
	250	0.07	0.39	1.41	0.040	2.88	0.41	0.328	0.96	0.51
	300	0.15	0.38	1.58	0.048	2.71	0.35	0.332	1.09	0.35
	325	0.14	0.42	1.25	0.050	2.69	0.32	0.304	1.32	0.44
	350	0.15	0.43	1.52	0.053	2.68	0.34	0.267	1.27	0.47
	375	0.15	0.41	1.29	0.049	2.69	0.34	0.300	1.23	0.35
S 37	0	0.15	0.41	0.89	0.048	2.60	0.34	0.020	1.23	0.31
Aug 1972	5	0.23	0.42	1.24	0.055	3.13	0.35	0.045	1.21	0.40
	10	0.21	0.41	0.93	0.055	4.20	0.34	0.131	1.21	0.46
	50	0.18	0.37	1.16	0.050	5.42	0.33	0.848	1.11	0.46
S 38	0	0.13	0.41	0.90	0.049	2.73	0.31	0.016	1.31	0.33
Aug 1972	5	0.24	0.41	1.75	0.060	3.38	0.34	0.092	1.22	0.46
	10	0.28	0.45	1.78	0.058	4.49	0.28	0.160	1.58	0.40
	50	0.26	0.35	1.25	0.067	5.03	0.30	0.919	1.16	0.42
S 39	0	0.12	0.42	0.91	0.050	2.39	0.30	0.020	1.37	0.45
Aug 1972	5	0.22	0.43	1.32	0.058	3.03	0.33	0.073	1.30	0.50
	10	0.41	0.46	1.24	0.058	4.31	0.36	0.258	1.30	0.37
	50	0.10	0.35	1.32	0.053	5.77	0.31	1.000	1.12	0.41
S 40	0	0.14	0.43	0.98	0.051	2.38	0.30	0.013	1.45	0.40
Aug 1972	5	0.41	0.45	1.03	0.058	4.24	0.31	0.123	1.47	0.55
	10	0.16	0.43	1.03	0.056	4.75	0.36	0.273	1.23	0.39
	50	0.21	0.37	1.70	0.068	5.38	0.27	0.764	1.37	0.46
S 41	0	0.19	0.47	0.88	0.049	2.30	0.33	0.031	1.43	0.69
Aug 1972	5	0.18	0.44	1.00	0.051	2.35	0.32	0.042	1.37	0.62
	10	0.41	0.47	0.97	0.059	3.09	0.35	0.112	1.35	0.52
	15	0.36	0.43	1.59	0.063	4.15	0.35	0.303	1.21	0.48
	25	0.37	0.45	1.83	0.068	3.76	0.36	0.306	1.27	0.43
	50	0.16	0.39	1.44	0.061	4.76	0.26	1.420	1.50	0.36
	75	0.31	0.40	2.64	0.061	4.24	0.27	-	1.44	-
	100	0.28	0.37	3.21	0.063	4.44	0.27	0.870	1.35	0.65
	125	0.47	0.34	3.81	0.079	3.36	0.28	0.749	1.23	0.80
	150	0.25	0.38	4.90	0.063	3.42	0.31	-	1.24	-
	175	0.11	0.38	4.90	0.052	3.09	0.31	0.497	1.22	-
	200	0.11	0.39	2.75	0.051	3.17	0.34	-	1.13	0.73
	225	0.14	0.41	1.44	0.051	2.81	0.33	0.328	1.24	0.53
	250	0.11	0.42	1.36	0.049	2.94	0.36	0.414	1.18	0.61
	275	0.11	0.41	1.43	0.049	2.86	0.39	0.411	1.06	0.60
S 42	0	0.16	0.42	1.03	0.051	2.36	0.32	0.024	1.32	0.52
Aug 1972	5	0.12	0.41	1.38	0.046	2.38	0.32	0.041	1.29	0.64
	10	0.45	0.46	1.10	0.059	4.48	0.33	0.195	1.39	0.38
	50	0.23	0.36	1.26	0.058	3.14	0.34	0.375	1.05	0.41
S 43	0	0.16	0.43	1.02	0.048	2.37	0.30	0.037	1.41	0.51
Aug 1972	5	0.13	0.41	1.00	0.048	2.46	0.31	0.037	1.32	0.48
	10	1.15	0.46	1.02	0.053	5.26	0.50	0.239	0.93	0.52
	50	0.30	0.26	1.86	0.043	3.58	0.24	0.940	1.06	0.53

Table D 7 continued

Cruise, station and date	Depth (m)	Ca/Al	K/Al	Fe/Al	Ti/Al	Si/Al	Mg/Al	Mn/Al	K/Mg	P/S
Cruise I (continued)										
S 45	0	0.14	0.45	0.89	0.049	2.25	0.34	0.028	1.33	0.44
Aug 1972	10	0.15	0.42	1.08	0.050	2.94	0.33	0.085	1.30	0.47
	25	0.24	0.41	1.30	0.042	3.24	0.29	0.178	1.44	0.42
	50	0.33	0.30	3.79	0.055	3.71	0.20	0.302	1.47	0.58
	75	0.25	0.25	5.06	0.049	3.20	0.21	0.338	1.22	0.64
	100	0.25	0.36	6,73	0.057	4.05	0.27	0.762	1.34	0.70
	150	0.18	0.33	7.70	0.048	3.25	0.28	0.892	1.16	1.35
	225	0.16	0.42	2.10	0.049	2.77	0.40	0.467	1.04	0.54
S 46	0	0.10	0.45	0.87	0.048	2.21	0.31	0.012	1.44	0.80
Aug 1972	5	0.13	0.44	0.96	0.050	2.23	0.31	0.017	1.44	0.72
	10	0.26	0.45	0.91	0.052	2.49	0.30	0.033	1.49	0.55
	15	0.23	0.46	0.99	0.049	2.83	0.33	0.131	1.40	0.51
	25	0.46	0.31	2.44	0.045	3.37	0.28	0.155	1.08	0.44
	50	0.38	0.17	5.11	0.047	3.52	0.14	0.096	1.22	0.72
	75	0.37	0.19	6.90	0.051	2.34	0.13	0.181	1.40	0.85
	100	0.28	0.31	19.20	0.068	4.24	0.25	0.570	1.23	0.85
River Ullensvang		0.47	0.28	1.38	0.075	2.41	0.39	0.020	0.72	0.76
River Espe		0.40	0.27	0.95	0.062	2.10	0.32	0.017	0.83	0.25
River Fosså		0.17	0.29	1.14	0.081	2.35	0.41	0.013	0.84	0.74
River Ringdalsvaan		0.06	0.29	0.61	0.041	1.64	0.16	0.028	1.87	0.23
Lake Sandvevann		0.13	0.49	1.27	0.069	2.23	0.26	0.010	1.89	0.85
River Opo (upper)		0.13	0.52	1.21	0.076	2.20	0.25	0.013	2.14	0.99
River Opo (lower)		0.13	0.53	1.15	0.072	2.23	0.25	0.011	2.08	0.91
Cruise II										
S 58	0	0.37	0.35	0.77	0.032	1.63	0.37	0.11	0.94	1.25
Sep 1973	5	1.16	0.49	1.26	0.037	3.02	0.56	0.22	0.87	0.84
	10	1.43	0.44	1.01	0.050	2.86	0.63	0.26	0.71	0.56
	20	1.71	0.38	0.92	0.056	3.04	0.48	0.22	0.79	0.55
	25	1.72	0.48	1.03	0.056	3.59	0.51	0.25	0.94	0.79
	30	3.39	0.45	1.15	0.067	4.47	0.67	0.52	0.68	0.50
	50	3.62	0.28	0.92	0.051	3.59	0.36	0.56	0.79	0.59
	70	3.58	0.42	1.13	0.055	3.13	0.52	0.57	0.81	0.62
	80	2.66	0.39	1.01	0.050	3.27	0.31	0.28	1.26	0.48
	90	2.41	0.33	1.03	0.042	2.70	0.39	0.29	0.85	0.69
	100	3.43	0.38	1.16	0.054	3.59	0.51	0.40	0.75	0.61
	125	2.56	0.45	1.33	0.047	3.15	0.74	0.30	0.61	0.51
	150	2.20	0.37	1.61	0.044	3.17	0.44	0.37	0.83	0.66
	200	1.18	0.37	1.11	0.042	2.52	0.38	0.25	0.98	0.66
	225	0.93	0.40	1.04	0.046	2.56	0.38	0.22	1.07	0.52
	250	1.19	0.42	1.07	0.039	2.57	0.42	0.35	1.02	0.41
S 59	0	0.30	0.33	0.66	0.031	1.55	0.22	0.04	1.50	1.83
Sep 1973	3	1.01	0.45	0.85	0.046	2.65	0.49	0.34	0.93	0.82
	8	0.77	0.42	1.10	0.063	3.24	0.49	0.20	0.85	0.66
	22	1.15	0.46	0.94	0.045	3.21	0.44	0.42	1.03	0.61
	50	3.09	0.22	1.06	0.050	2.47	0.54	0.75	0.41	0.73
	75	2.36	0.36	1.21	0.049	3.25	0.47	0.56	0.76	0.71
	100	1.88	0.35	1.10	0.044	2.90	0.44	0.59	0.80	0.77
	150	2.37	0.23	2.63	0.042	2.13	0.40	0.75	0.59	1.05
	200	1.69	0.51	1.64	0.050	2.45	0.67	0.50	0.76	0.45
	250	0.83	0.39	1.44	0.039	2.38	0.58	0.70	0.67	0.80
	300	0.69	0.36	1.05	0.049	2.63	0.36	0.58	1.09	0.72
	310	2.89	0.34	1.28	0.054	3.07	0.58	0.98	0.58	0.80
	330	0.48	0.36	1.01	0.047	2.52	0.29	0.69	1.23	0.57
	350	0.65	0.39	0.96	0.040	2.44	0.30	0.69	1.14	0.74
	385	0.71	0.38	0.91	0.038	2.50	0.46	0.93	0.84	0.68

Table D 7 continued

Cruise, station and date	Depth (m)	Ca/Al	K/Al	Fe/Al	Ti/Al	Si/Al	Mg/Al	Mn/Al	K/Mg	P/S
Cruise II (continued)										
S 63	0	0.75	0.35	0.68	0.025	1.51	0.32	0.07	1.08	1.50
Sep 1973	5	1.08	0.42	1.22	0.055	2.62	0.63	0.32	0.68	0.84
	10	0.61	0.49	1.20	0.052	3.17	0.73	0.33	0.67	0.79
	20	1.34	0.44	1.19	0.029	3.10	0.72	0.71	0.62	0.85
	30	1.04	0.23	1.44	0.036	2.46	0.45	0.63	0.50	2.10
	40	1.54	0.20	3.20	0.080	3.62	0.46	0.20	0.44	1.45
	50	3.53	0.11	2.65	0.050	2.76	0.29	0.06	0.37	0.88
	60	3.72	0.10	2.72	0.045	2.50	0.19	0.07	0.53	0.65
	70	3.18	0.09	1.92	0.047	1.43	0.22	0.02	0.39	0.96
	80	2.80	0.09	1.93	0.046	1.16	0.20	0.02	0.42	1.10
	90	2.78	0.08	2.23	0.047	1.25	0.23	0.04	0.36	1.03
	100	2.66	0.12	3.11	0.053	1.64	0.32	0.06	0.39	0.91
	110	2.58	0.22	4.76	0.054	2.64	0.48	0.14	0.44	0.69
	120	2.42	0.28	4.80	0.059	2.86	0.49	0.23	0.56	0.74
	130	2.71	0.28	6.88	0.045	3.03	0.65	0.36	0.43	1.15
S 64	0	0.75	0.45	1.28	0.030	2.01	0.30	0.04	1.51	2.48
Sep 1973	5	1.46	0.36	1.10	0.034	2.65	0.27	0.25	1.34	1.69
	10	1.62	0.21	1.10	0.032	2.13	0.12	0.44	1.80	1.67
	20	8.37	0.26	1.35	0.038	2.17	0.49	0.43	0.53	1.27
	30	2.13	0.15	1.65	0.030	1.53	0.35	0.13	0.44	3.92
	40	2.82	0.14	2.72	0.061	2.27	0.20	0.04	0.68	1.58
Cruise III										
S 69	0	2.44	0.28	3.16	0.068	8.57	0.17	0.02	1.68	0.83
Apr 1974	5	1.27	0.23	1.13	0.066	6.71	0.14	0.24	1.59	0.63
	10	-	-	1.05	0.035	8.41	-	0.55	-	-
	25	0.32	0.20	0.60	0.034	26.10	0.11	1.75	1.90	0.75
	50	0.71	0.36	1.30	0.035	18.80	0.26	0.67	1.36	1.45
	100	0.92	0.32	1.85	0.083	7.65	0.19	0.50	1.71	0.84
	200	-	-	1.28	0.068	5.79	-	0.26	-	-
	250	0.65	0.43	1.35	0.054	8.70	0.35	0.28	1.22	1.08
	300	0.48	0.44	1.63	0.051	4.64	0.36	0.47	1.23	1.06
	325	-	-	1.77	0.044	3.48	-	0.64	-	-
	340	0.30	0.44	1.61	0.041	4.14	0.42	0.63	1.05	1.37
S 71	0	0.40	0.18	2.13	0.043	5.47	0.13	0.02	1.44	4.01
Apr 1974	5	0.82	0.20	1.29	0.039	4.93	0.10	0.13	1.91	0.83
	10	2.93	0.26	0.82	0.058	29.92	0.26	0.60	0.97	0.48
	25	1.48	0.23	0.87	0.043	18.77	0.35	0.98	0.67	0.45
	50	1.34	0.24	1.79	0.050	18.55	0.22	0.36	1.10	2.00
	100	0.73	0.35	2.15	0.049	6.74	0.22	0.43	1.56	1.39
	150	0.79	0.40	1.54	0.051	5.54	0.38	0.28	1.05	1.16
	200	0.41	0.42	1.56	0.047	4.64	0.37	0.26	1.16	1.27
	250	0.48	0.42	1.89	0.046	4.15	0.36	0.55	1.16	1.76
	300	0.39	0.42	1.49	0.046	3.19	0.38	0.54	1.10	1.56
	350	0.38	0.45	1.35	0.042	3.50	0.43	0.70	1.05	1.67
	375	0.25	0.43	1.25	0.041	3.19	0.41	0.61	1.06	1.79
S 72	0	0.21	0.13	1.70	0.040	1.24	0.08	0.01	1.48	9.14
Apr 1974	5	1.46	0.13	2.91	0.032	6.91	0.16	0.08	0.81	1.67
	10	2.13	0.14	2.18	0.034	10.09	0.23	0.17	0.61	0.52
	25	1.36	0.25	1.51	0.030	20.42	0.10	0.63	2.42	0.58
	50	2.59	0.19	3.41	0.062	9.59	0.08	0.15	2.33	1.37
	75	-	-	8.73	0.065	7.16	-	0.24	-	-
	100	1.21	0.29	8.46	0.049	3.70	0.19	0.50	1.58	3.16
	110	1.10	0.30	8.77	0.049	5.44	0.12	0.37	2.51	2.69
S 73	0	0.29	0.17	2.72	0.075	1.23	0.06	0.01	2.73	12.43
Apr 1974										

APPENDIX E

Publications

Skei, J.M., N. B. Price, S. E. Calvert and H. Holtedahl, 1972.
The distribution of heavy metals in sediments of Sörfjord, West Norway.
Water, Air and Soil Poll., 1, 452-461.

Skei, J.M., N. B. Price and S. E. Calvert, 1973.
Particulate metals in waters of Sörfjord, West Norway.
Ambio, 2, 122-124.

Price, N.B. and J. M. Skei, 1975.
Areal and seasonal variations in the chemistry of suspended particulate matter in a deep water fjord.
Estuar. Coast. Mar. Sci., in press.

Estuarine and Coastal Marine Science (1975) 3, [illegible]

Areal and Seasonal Variations in the Chemistry of Suspended Particulate Matter in a Deep Water Fjord

N. Brian Price and J. M. Skei

Grant Institute of Geology, King's Buildings, West Mains Road, Edinburgh, U.K.

Received 25 September 1974

Areal and seasonal studies of the major elements (Si, Al, Ti, Ca, Mg, Fe, Mn, K, P and S) and minor elements (Zn and Pb) in suspended particulate matter from five water profiles in Hardangerfjorden, Norway have been made to assess variations in productivity and the behaviour of elements associated with organic matter. Attempts have been made to partition these elements between the terrigenous, skeletal, organic and authigenic constituents. Elements denoting terrigenous matter, especially Al, are situated at or above the pycnocline during times of high river runoff. In spring when runoff is minimal and the upper waters are essentially isohaline, aluminosilicates occupy the zone of maximum biological productivity, as seen by high particulate P and S, and may be intimately associated with plankton. Ca and especially biogenous Si are also high in these upper waters.

An assessment of the decomposition of the organic matter during drying and storage has been made by measuring differences in element concentrations between distilled water washed and unwashed samples. Considerable differences in P, Mn, Zn and Pb have been noted, and element losses in the upper waters are considerably higher (40–90%) than in the deeper waters (0–30%). These observations, together with the pronounced falloff in concentration of the same elements between the surface and underlying waters, suggests that organic P, Mn, Zn and Pb could be rapidly released into waters of the euphotic zone and only a small proportion of these organically bound elements will survive fallout to the seabed.

Particulate Al is uniformly distributed in the deeper waters and gives the impression that little or no recent resuspension of bottom sediment aluminosilicates has occurred. However, Mn concentrations increase below 400–450 m and can exceed Al concentrations. It is argued that much of this Mn represents the residuum of resuspended particulate matter, comprising both aluminosilicates and authigenic Mn. Preferential resettling of aluminosilicates from the bottom nepheloid layers and the deposition of Mn in ocean sediments is discussed.

Introduction

In recent years there has been a growing awareness of the importance of studies of suspended particulate matter in marine waters. While these studies have improved our understanding of sedimentation processes, unfortunately, the majority of investigations consider particulate matter only in terms of gravimetric variations of total particulate matter and as a consequence have limited application. Few workers investigate the mineralogy of particulate matter

and still less study its chemical composition and the partitioning of elements between its constituent parts. Hence it is difficult to realistically compare new and comprehensive data with limited information based perhaps on a knowledge of concentrations and behaviour of one or two elements.

In the paper we intend to examine the composition of the various constituents of particulate matter, especially elements associated with organic matter of a deep and well stratified fjord—Hardangerfjorden, Norway. With a knowledge of hydrography we intent to study both the areal and seasonal changes in particulate matter in the upper waters. Not least amongst these will be a study of the chemistry of the particulate matter as it is influenced by variations in productivity. Water exchange between outlying and fjord waters is a common phenomenon in many fjords. The effects of this may affect bottom sediment resuspension in the lower waters. It is hoped that a study of the particulate matter with special reference to the resuspension of terrigenous and authigenic constituents, especially Mn, will add to our knowledge of sedimentation processes in marine basins.

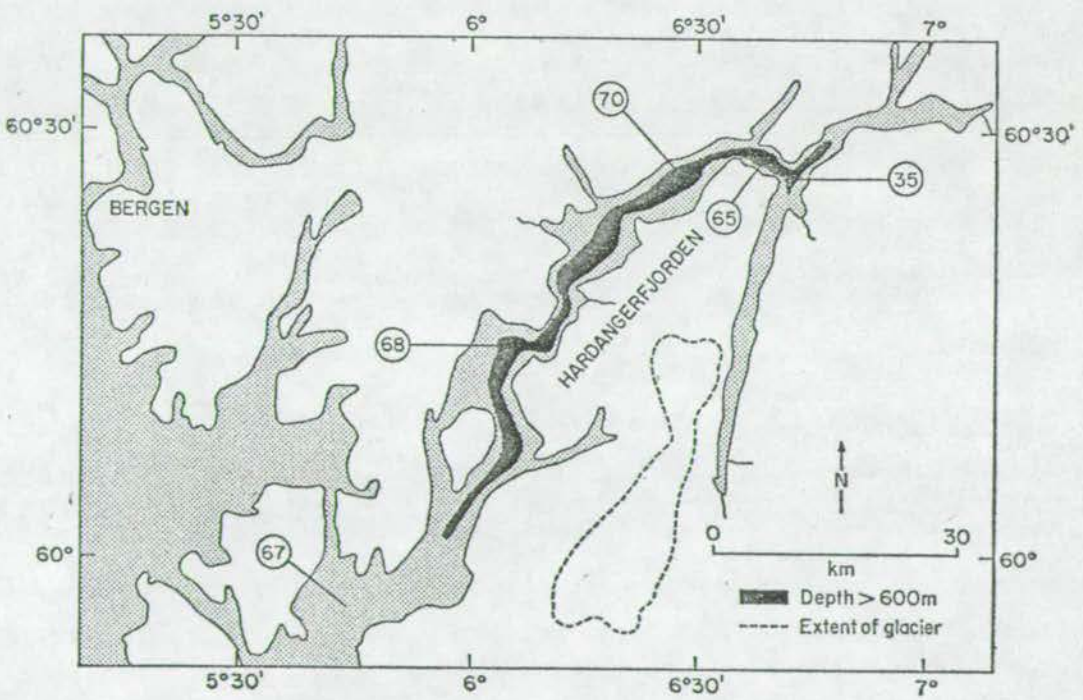


Figure 1. Location of sampling stations in Hardangerfjorden, Norway.

Hardangerfjorden—general situation

Hardangerfjorden is situated in south west Norway some 60 km south of Bergen (Figure 1). It is 135 km long and 5–10 km wide and trends NE–SW. Most rivers entering the fjord do so near its head via a series of secondary fjords, and tend to drain a mountainous terrain composed largely of acid gneisses and altered siliceous sediments.

While its maximum depth is recorded at 870 m, that is in its inner part, in reality the fjord can be subdivided into three basins, with intervening sills or thresholds, (Figure 2) of increasing depth towards the northeast. The most noticeable of the thresholds is

the outer sill of 180 m which separates Hardangerfjorden from coastal waters. The bottom sediments comprise fine grained silts and occasional sands which appear to have accumulated either as local turbidites (Holtedahl, 1965) or from more normal sedimentation processes.

The fjord is well stratified especially during the summer months when the runoff is highest ($3{\cdot}0 \times 10^9$ m^3/month^{-1}) (Saelen, 1967). It is also known that the displacement of its lower waters can occur through periodic and partial flushings (Saelen, 1967). The water circulation will be more fully described below.

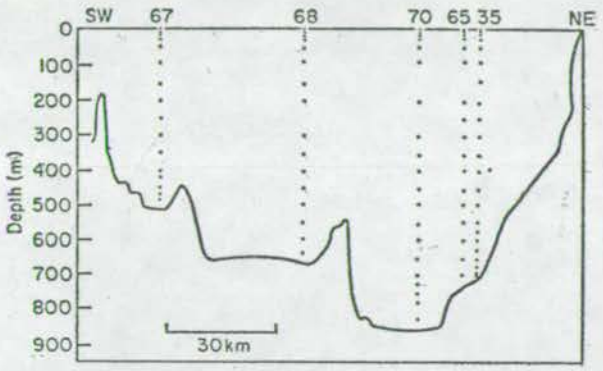


Figure 2. A longitudinal bottom profile of Hardangerfjorden, Norway, drawn along the deepest part of the fjord. Sampling depths are indicated by solid circles.

Sampling and analysis

Water was collected from five water profiles (Figure 2) with 7 l N.I.O. polypropylene water bottles. About 4–5 l of this water was immediately filtered through 0·4 μ ' Nuclepore ' membrane filters using plexiglas filter holders and a totally enclosed N_2 gas pressure filtering system to prevent contamination. The samples were than air dried prior to their analysis. With particulate matter collected in 1972 and 1973 the filters were washed free of sea salt prior to their analysis. Analysis of material collected in 1974 was performed firstly on unwashed filters and then repeated after the samples had been washed in membrane distilled water (~200 ml).

The samples were analysed by X-Ray emission analysis following the method of Price & Calvert (1973), and Price (1974*a*, *b*). Zn and Pb were determined by referring their respective peak intensities (i.e. Zn $K_{\alpha 1}$ and Pb $L_{\alpha 1}$) to those of a series of synthetic standards of preweighed deposits of $Zn_2Fe(CN)_6$ and $PbCrO_4$ diluted into an argillaceous base of 1 μm grain size. The precision of analysis for the various elements is given in Tables 1 and 3.

The analysis of unwashed samples necessarily includes those elements held in evaporated sea salts. Unfortunately, due to some dissociation of some of these elements under X-rays (e.g. Cl) it was not possible to assess accurately the contribution that sea-salt K, Ca, Mg and S made to the analysis of the particulate matter. For this reason, these elements were analysed on washed filters and the resultant analyses for K, Ca, Mg and S are regarded as the concentration levels of particulate matter. Sea-salt Cl^- was shown to be completely removed by washing. The repeated analysis of other elements after washing and the amounts of elements removed from the filters may provide some estimate of the degree of alteration that the particulate matter has suffered by degradation and other processes, especially on organic substances, during the drying and storage of material prior to its analysis.

Hydrography

It is convenient to describe the hydrography of Hardangerfjorden in terms of the upper waters (100 m depth) where seasonal changes in salinity and temperature are likely to occur and deep waters which are not directly influenced by seasonal variations, but nevertheless may show periodic change (Saelen, 1967). Temperature and salinity measurements were taken only in the uppermost 100 m of water due to the limitations of the S–T measuring bridge (N.I.O.). Dissolved O_2 (ml/l) was determined at all depths.

Variations with respect to depth of S–T measurements for stations H67, H68, H70, taken during April 1974 are small. In contrast, the hydrography of the upper 100 m of water of three inner stations H35, H65 and H70 (Figure 2) sampled during summer, autumn and spring, respectively, shows considerable change (Figure 3). While the temperatures at different seasons can show much variation, especially in the surface waters (<10 m), the change in salinity (Figure 3) usually dictates the density structure of waters and the position of the pycnocline. Seasonal variations in salinity for uppermost 40 m of water can be described in terms of dilution by river runoff. A near surface halocline occurring at 5–10 m is most marked in summer (H35), but becomes less prominent and slightly deeper in autumn when runoff is less (H65). In early spring (H70) the upper waters are essentially isohaline due to a negligible runoff before the melting of snow. The general increase of salinity in waters between 10–40 m during summer, which implies some further mixing of saline waters, is also paralleled in the S profile at other seasons. At 100 m the salinity is very similar to that observed by Saelen in 1955–56 (S=34·7‰).

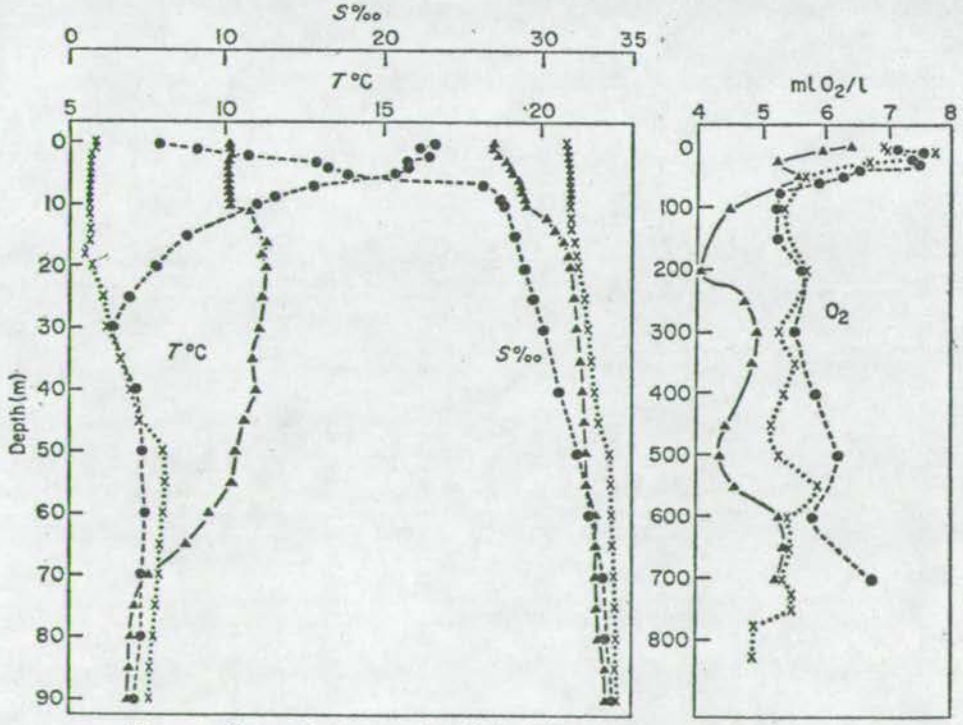


Figure 3. Seasonal changes in salinity (S‰), temperature (T °C) and dissolved oxygen, (ml O_2/l) in the inner parts of Hardangerfjorden, Norway. Note S–T S–T profiles represent only the upper 90 m of water. – – ● – – ● – –, H35 (August 1972); —▲—▲—, H65 (October 1973); · · · × · · · × · · ·, H70 (April 1974).

The hydrographic features of the deeper waters have not been assessed. Nevertheless, detailed observations by Saelen (1962, 1967) indicate that some intermediate or deep water renewal can take place. It appears that while flushing of water at different depths and at different times is a common feature of the fjord, it may not always extend into the deepest waters.

Dissolved oxygen concentrations in the surface waters are higher in spring and summer than in autumn (Figure 3). The variation in dissolved oxygen in the midwaters are considerable and appear quite irregular with respect to depth. Such changes may indicate introduced water of different origins as demonstrated by Saelen (1967). Oxygen concentrations between 100 m and 600 m in October 1973 are smaller than at other times. This feature of lower oxygen contents in the midwaters is characteristic of many fjords (Thompson & Barkey, 1938; Pickard, 1961, 1970; Gade, 1973; Svendsen, 1973) and is thought to be due either to a combination of runoff conditions and biological demand or to the upward displacement of deeper lying oxygen poorer water by flushing.

Profiles of dissolved O_2 for stations H35, H65 and H70 show an abundance of O_2 at depth (Figure 3) and there is no indication of bottom anoxic conditions as occurs in many other fjords (Ström, 1936).

Results

The concentrations (µg/kg) of the particulate major elements and minor elements, Pb and Zn are given in Tables 1 and 3. Table 1 represents analysis of Si, Al, Ti, Mg, Ca, K, Fe, Mn, S and P in particulate matter washed in distilled water to remove evaporated sea-salt. However, the particulate matter collected in April 1974 (H67, H68, H70) had been previously analysed for major elements, Zn and Pb, prior to washing and Table 3 represents the analyses on these unwashed samples and the difference in composition between them and the same samples after they had been washed.

Because concentrations of elements, usually regarded as representing terrigenous and biogenous skeletal matter, e.g. Si, Ti, Al and Fe (Price & Calvert, 1973; Price, 1974*a*) are unaffected by the washing, we assume in the first instance that K, Mg and Ca concentrations of washed filters are held in the same constituents and are also resistant to washing and hence are regarded as maximum concentrations.

Terrigenous constituents

Following Spencer & Sachs (1970); Feely *et al.* (1971) and Price & Calvert (1973), the amount of terrigenous aluminosilicates at any level in water profiles can be assessed from concentrations of particulate Al. The areal distribution of Al in the upper waters during April 1974 (H67, H68 and H70) is not always well defined, except at 25 m where the three stations show marked enrichments and some westerly increase. Seasonal variations in particulate aluminosilicates are very much more distinct and tend in the upper waters to closely follow the hydrography. Where a distinct pycnocline is developed as in Station H35 (August 1972), Al concentrations are extremely high, with a surface value of 36·51 µg/kg, but decrease markedly between 0 m and 5 m. At other seasons when runoff is less, especially in spring (Saelen, 1967), the amounts of particulate Al are smaller and are not so confined to the uppermost waters.

Particulate Ti in most samples closely follows Al and is in accordance with the concept that the two elements are closely associated in clay substances (Goldschmidt, 1954). Further, the mean Ti/Al ratio [0·04, (Table 2)] approximates to the value of the bottom sediments

TABLE 1. Concentrations (μg/kg) of major elements of washed particulate matter from Hardangerfjorden, Norway

Depth (m)	Si	Al	Ti	Mg	Ca	K	Fe	Mn	S	P
Station H35 (depth = 730 m) (August 1972)										
0	122·69	36·51	1·83	10·46	8·89	14·27	32·06	0·78	16·91	7·16
5	11·92	2·54	0·12	1·01	3·42	1·21	2·38	0·33	3·13	1·25
10	27·20	3·34	0·16	1·40	2·12	1·38	3·33	0·48	15·66	5·10
25	13·38	2·15	0·18	0·86	1·72	0·97	5·00	0·63	5·78	2·43
50	8·93	2·18	0·15	0·58	0·92	0·88	2·08	0·56	1·97	0·76
100	5·34	1·59	0·08	1·79	0·96	0·70	1·91	0·27	1·00	0·48
150	5·33	1·89	0·12	0·55	0·61	0·84	4·09	0·34	1·00	0·45
200	6·43	2·52	0·14	0·79	0·53	1·14	3·00	0·47	0·96	0·40
250	12·79	5·46	0·23	1·01	0·80	2·00	5·37	1·21	0·98	0·61
300	1·48	0·97	0·06	0·31	0·31	0·41	1·51	0·23	0·38	0·19
350	7·21	3·17	0·16	1·02	0·75	1·42	3·71	0·89	1·10	0·39
400	7·79	3·11	0·16	0·87	0·57	1·24	4·75	0·71	0·86	0·43
450	7·88	3·05	0·17	0·90	0·54	1·31	5·06	1·01	0·92	0·35
500	8·07	3·11	0·14	1·02	0·46	1·34	3·64	1·63	0·82	0·36
550	10·12	3·90	0·20	1·09	0·96	1·72	4·94	2·74	1·46	0·56
575	4·80	2·03	0·10	0·67	0·75	0·93	2·96	1·56	0·86	0·25
600	7·10	2·90	0·15	0·88	0·72	1·47	4·97	2·02	1·29	0·48
625	8·86	3·28	0·15	1·19	0·59	1·45	4·37	2·77	1·53	0·39
650	7·75	3·23	0·18	0·76	0·87	1·43	4·31	3·40	1·72	0·47
675	9·11	3·55	0·19	1·07	0·76	1·43	5·93	4·12	1·70	0·50
700	7·66	3·34	0·15	1·17	0·46	1·58	4·86	6·65	2·07	0·53
Station H65 (depth = 740 m) (October 1973)										
0	12·30	3·20	0·16	1·08	3·36	1·46	3·55	0·56	3·46	2·62
5	13·79	3·96	0·17	2·17	6·03	1·97	3·88	1·07	5·12	3·43
10	13·44	3·07	0·16	3·27	4·69	1·82	3·47	0·90	7·81	4·33
25	7·70	2·05	0·10	1·16	4·16	1·07	2·29	0·44	2·74	1·63
50	5·56	1·46	0·08	0·92	3·64	0·67	1·41	0·37	1·87	0·99
100	2·15	0·78	0·05	0·20	0·96	0·25	0·80	0·20	0·91	0·39
200	4·86	1·55	0·07	0·78	2·09	0·74	1·63	0·30	0·62	0·36
250	6·52	2·38	0·11	0·96	2·68	1·02	2·58	0·71	0·79	0·45
300	2·16	0·74	0·03	0·36	0·77	0·43	0·69	0·08	0·47	0·16
350	7·37	2·74	0·13	1·25	2·13	1·16	2·78	0·78	1·17	0·42
400	3·87	1·48	0·07	0·52	1·04	0·61	1·46	0·56	0·55	0·27
500	2·41	0·85	0·03	0·40	0·87	0·35	1·00	0·46	0·58	0·16
550	3·06	1·22	0·05	0·65	0·91	0·52	1·33	0·90	0·58	0·23
600	1·16	0·45	0·02	0·18	0·45	0·17	0·50	0·54	0·94	0·17
650	2·09	0·73	0·04	0·40	0·93	0·31	1·07	1·48	1·28	0·20
Station H70 (depth = 860 m) (April 1974)										
0	84·67	4·88	0·21	0·67	4·09	1·40	4·25	0·44	6·21	3·51
5	83·76	3·71	0·14	0·86	2·89	0·82	3·61	1·11	4·91	3·68
25	133·88	4·02	0·23	1·15	4·85	0·88	3·37	0·86	4·61	3·68
50	42·26	2·50	0·09	0·49	0·58	0·73	2·58	0·53	0·86	0·80
100	20·48	2·80	0·12	0·81	0·86	1·02	3·05	0·21	0·69	0·44
200	14·91	2·63	0·10	0·65	1·07	1·02	3·18	0·25	0·59	0·41
300	10·99	2·15	0·09	0·53	0·68	0·82	2·88	0·34	0·62	0·35
350	7·82	1·92	0·19	1·10	2·40	0·79	2·90	0·35	0·61	0·35
400	6·08	1·39	0·15	0·34	0·43	0·35	1·80	0·23	0·54	0·20
450	11·36	2·72	0·14	n.a.	n.a.	n.a.	3·84	n.a.	n.a.	n.a.
500	13·51	3·00	0·19	0·81	1·27	1·16	4·23	0·69	0·76	0·37
550	16·79	3·47	0·25	0·75	2·44	1·11	4·34	0·85	1·08	0·47
600	7·13	1·66	0·06	0·48	0·61	0·65	2·96	1·16	0·58	0·29
650	8·92	1·99	0·10	0·68	0·94	0·81	3·05	1·56	0·86	0·29

TABLE 1.—*continued*

Depth (m)	Si	Al	Ti	Mg	Ca	K	Fe	Mn	S	P
Station H70 (depth=860 m) (April 1974)										
700	11·10	2·43	0·12	0·73	0·80	0·91	3·96	0·87	0·59	0·39
725	9·72	2·28	0·14	0·69	0·96	0·95	3·43	2·67	0·58	0·34
750	11·31	3·23	0·21	1·09	1·07	1·33	5·33	4·65	0·62	0·41
825	8·76	2·62	0·12	1·10	0·81	1·20	4·28	5·28	0·52	0·41
Station H68 (depth=660 m) (April 1974)										
0	31·36	2·24	0·11	1·08	2·23	0·53	3·00	0·13	3·80	2·05
5	26·75	1·70	0·10	0·43	1·71	0·38	1·60	0·19	3·18	1·76
10	31·70	2·08	0·11	1·26	3·02	0·55	1·57	0·52	4·56	2·48
25	249·50	8·12	0·55	4·44	8·40	2·09	5·81	0·83	9·88	6·37
50	38·64	2·53	0·08	0·99	1·57	0·85	2·54	0·27	0·99	0·79
100	11·78	2·61	0·08	0·86	0·64	1·12	2·58	0·17	0·62	0·33
150	13·09	3·24	0·10	1·07	1·89	1·37	2·98	0·27	0·73	0·44
200	11·25	2·32	0·09	0·38	1·39	1·01	2·22	0·28	0·93	0·22
300	7·21	1·76	0·07	0·64	1·12	0·77	2·54	0·46	0·55	0·29
350	4·58	2·22	0·09	0·91	1·10	1·08	3·59	0·43	0·55	0·43
400	5·64	2·76	0·09	0·72	0·67	1·23	3·00	0·76	0·38	0·35
500	10·47	3·83	0·16	1·10	2·27	1·55	4·00	0·97	0·69	0·38
550	7·64	2·86	0·08	0·88	0·36	1·16	3·02	0·56	0·28	0·24
600	20·42	7·58	0·26	2·14	2·73	3·44	8·70	1·56	0·46	0·51
640	21·85	8·04	0·29	2·51	3·99	3·62	7·80	1·88	0·53	0·51
Station H67 (depth=520 m) (April 1974)										
0	14·53	2·12	0·20	1·00	2·45	0·54	3·18	0·08	1·95	0·93
5	82·57	5·67	0·64	2·98	16·05	1·26	5·09	0·39	6·79	3·35
10	62·04	2·93	0·09	1·72	2·47	0·62	2·62	0·40	4·09	3·21
25	442·78	13·34	0·67	7·31	12·23	2·93	8·85	0·44	13·57	7·44
50	32·11	3·49	0·25	0·86	1·38	1·03	4·78	0·33	1·45	1·00
100	12·41	3·75	0·14	1·11	1·47	1·46	4·44	0·31	0·53	0·55
150	10·14	4·09	0·18	0·97	1·27	1·45	3·69	0·30	0·49	0·35
200	7·88	3·14	0·09	0·77	0·92	1·06	2·53	0·24	0·49	0·34
250	5·93	2·90	0·13	0·80	1·10	1·06	3·18	0·29	0·50	0·30
300	6·76	2·29	0·11	0·61	1·70	0·77	2·68	0·29	0·44	0·65
350	5·53	2·74	0·11	0·78	0·91	1·07	3·77	0·77	0·46	0·35
400	5·16	2·26	0·13	0·62	1·15	0·99	n.a.	n.a.	0·50	0·41
425	6·68	3·16	0·10	0·92	1·80	1·23	4·28	1·49	0·47	0·46
475	6·74	2·52	0·10	0·93	1·23	1·02	3·60	1·17	0·63	0·38
[a] Analytical precision represents the percentage deviation of 6 replicate analyses.										
[a] Analytical precision:	6%	2%	5%	3%	2·5%	2%	1·5%	4%	3%	4%

n.a.: not analysed.

(Ti/Al=0·07). However, some increase in ratio occurs especially in the upper 25 m of the water column (Ti/Al=0·03—0·113) and will be discussed in detail below.

It is likely that the bulk of particulate K and Mg also resides in alumino silicates (Price & Calvert, 1973). Their respective ratios for most waters (Table 2) are similar to that seen in the underlying sediments (K/Al=0·38; Mg/Al=0·26) and river water particulate matter entering the fjord (K/Al=0·38; Mg/Al=0·30, Table 2). Table 2 clearly shows that K/Al ratios are lower and Mg/Al ratios higher in the uppermost 25 m of water collected in spring 1974 with the exception of station H70 where Mg/Al ratios remain constant with depth and here conform to the pattern of Ti/Al ratios. However, there does not appear to be

TABLE 2. Ratios of particulate Ti, Mg, K, Fe and Si with respect to Al and the concentrations of biogenous Si (μg/kg) in washed particulate matter from Hardangerfjorden, Norway

Depth (m)	Ti/Al	Mg/Al	K/Al	Fe/Al	Si/Al	Biogenous Si
0	0·050	0·42	0·44	0·88	3·36	42·4
5	0·047	0·40	0·48	0·94	4·70	6·3
10	0·048	0·61	0·47	1·00	8·14	19·9
25	0·084	0·40	0·45	2·33	6·22	8·7
50	0·069	0·27	0·40	0·95	4·10	4·1
100	0·050	1·50	0·81	1·20	3·36	1·8
150	0·063	0·29	0·44	2·16	2·82	1·2
200	0·056	0·31	0·45	1·19	2·55	0·9
250	0·042	0·30	0·37	0·98	2·34	0·8
300	0·062	0·32	0·42	1·56	1·53	0·0
350	0·051	0·32	0·45	1·17	2·28	0·3
400	0·051	0·28	0·40	1·53	2·50	1·0
450	0·056	0·30	0·43	1·66	2·58	1·2
500	0·045	0·33	0·43	1·18	2·59	1·2
550	0·051	0·28	0·44	1·27	2·59	1·6
575	0·049	0·32	0·46	1·46	2·36	0·3
600	0·052	0·30	0·51	1·37	2·45	0·7
625	0·046	0·36	0·44	1·33	2·70	1·6
650	0·056	0·24	0·44	1·33	2·46	0·6
675	0·054	0·30	0·40	1·67	2·57	1·3
700	0·045	0·35	0·47	1·46	2·29	0·3
Station H65						
0	0·050	0·34	0·46	1·11	3·47	5·3
5	0·043	0·55	0·50	0·98	3·48	5·1
10	0·052	1·07	0·59	1·13	4·38	6·7
25	0·049	0·57	0·52	1·12	3·76	3·2
50	0·055	0·63	0·46	0·97	3·81	2·4
100	0·064	0·26	0·32	1·03	2·76	0·4
200	0·045	0·50	0·48	1·05	3·14	1·5
250	0·046	0·40	0·43	1·08	2·74	1·3
300	0·041	0·49	0·58	0·93	2·92	0·5
350	0·047	0·46	0·42	1·01	2·69	1·3
400	0·047	0·35	0·41	0·99	2·61	0·6
500	0·034	0·47	0·41	1·18	2·87	0·5
550	0·041	0·53	0·43	1·08	2·51	0·4
600	0·044	0·40	0·38	1·11	2·58	0·2
650	0·055	0·55	0·43	1·47	2·76	0·5
Station H70						
0	0·020	0·13	0·27	0·87	17·35	73·9
5	0·038	0·23	0·22	0·97	22·58	75·6
25	0·057	0·26	0·20	0·84	33·30	125·0
50	0·036	0·20	0·29	1·03	16·90	36·8
100	0·032	0·29	0·36	1·09	7·31	14·3
200	0·038	0·24	0·38	1·21	5·67	9·1
300	0·042	0·24	0·37	1·34	5·11	6·3
350	0·099	0·57	0·37	1·51	4·07	3·6
400	0·108	0·34	0·35	1·30	4·37	3·0
450	0·051	—	—	1·41	4·18	5·4
500	0·063	0·27	0·39	1·41	4·50	7·0
550	0·072	0·22	0·32	1·25	4·84	9·2
600	0·036	0·28	0·39	1·78	4·36	3·5
650	0·050	0·30	0·36	1·53	4·48	4·5
700	0·049	0·29	0·36	1·63	4·57	5·8
725	0·061	0·28	0·39	1·50	4·26	4·7
750	0·068	0·31	0·38	1·65	3·50	4·2
825	0·046	0·39	0·42	1·63	3·34	3·0

TABLE 2.—*continued*

Depth (m)	Ti/Al	Mg/Al	K/Al	Fe/Al	Si/Al	Biogenous Si
Station H68						
0	0·049	0·48	0·23	1·34	14·00	26·7
5	0·059	0·25	0·22	0·94	15·74	23·0
10	0·053	0·61	0·26	0·76	15·24	27·1
25	0·068	0·55	0·23	0·72	30·73	231·6
50	0·032	0·39	0·29	1·00	15·30	33·1
100	0·031	0·33	0·37	0·89	4·51	6·0
150	0·031	0·33	0·37	0·92	4·04	6·0
200	0·039	0·16	0·36	0·96	4·85	6·0
300	0·040	0·36	0·38	1·44	4·10	6·2
350	0·041	0·41	0·37	1·62	1·47	0·0
400	0·033	0·26	0·37	1·09	2·04	0·0
500	0·042	0·29	0·38	1·04	2·73	2·0
550	0·028	0·31	0·39	1·06	2·67	1·4
600	0·034	0·28	0·41	1·15	2·69	3·7
640	0·035	0·31	0·42	0·97	2·72	4·2
Station H67						
0	0·094	0·47	0·28	1·58	6·86	9·9
5	0·113	0·53	0·21	0·94	14·56	70·1
10	0·031	0·59	0·21	1·56	21·18	55·6
25	0·050	0·55	0·20	0·73	33·19	413·4
50	0·072	0·25	0·30	1·41	9·20	24·4
100	0·037	0·30	0·35	1·24	3·31	4·2
150	0·044	0·23	0·34	0·90	2·48	1·1
200	0·029	0·25	0·32	0·81	2·51	1·0
250	0·045	0·28	0·34	1·14	2·04	0·0
300	0·048	0·27	0·33	1·18	2·95	1·7
350	0·040	0·28	0·34	1·32	2·02	0·0
400	0·058	0·27	0·36	1·39	1·55	0·0
425	0·032	0·29	0·36	1·32	2·11	0·0
475	0·040	0·37	0·39	1·46	2·67	1·2
River water (mean)						
	0·072	0·30	0·38	1·10	2·25	—
Sediments (mean)						
	0·070	0·26	0·38	0·54	3·50	—

any systematic seasonal trend in these ratios except that some near surface water (e.g. station H35, 10–50 m) show higher Ti/Al and Mg/Al values. Normal ratios are encountered in the aluminosilicate rich surface waters of this station.

These changes in elemental ratios, e.g. Mg/Al, K/Al ratios between the upper and lower waters and also between the inner and outer parts of the fjord may relate to differences in the composition of terrigenous minerals in the particulate matter.

Within the bottom waters some enrichment of Al occurs, particularly in station H68. Enrichment of Al close to the seabed is likely to imply resuspension of aluminosilicates from the seabed. The constant value of Al in the lower water profiles of all other stations suggests little disturbance and resuspension of aluminosilicates by currents induced by flushing or other means. During flushing Haakstad (170) has recorded current measurements of 20 cm/s^{-1} near the outer sill of Hardangerfjorden. The ratios of Ti/Al, Mg/Al and K/Al are no different in the deepest waters than in most overlying waters. There is however some increase in Ti/Al ratios in station H70 between 400–550 m where the mean Ti/Al is 0·08.

Variations in biogenous silicon and calcium

Terrigenous silicates in the surface sediments of the fjord have been measured and show Si/Al ratios of 3·5 which indicates a considerable amount of quartz in the samples; this has been confirmed by mineralogical investigations. However, Si/Al ratios of particulate aluminosilicates in fjord waters from the same region as Hardangerfjorden are generally lower, i.e. Si/Al=2·5 (Taylor, 1974) and are similar to the Si/Al ratios for river particulate matter entering Hardangerfjorden (Si/Al=2·2). We consider that any Si concentrations occurring in particulate matter in excess of a Si/Al ratio of 2·2 occurs as biogenous silicon (Table 2).

The results in Table 2 for the upper waters of the fjord show a marked enrichment in the excess or biogenous silica, as defined above. The content of quartz in this particulate matter was found to be very small in relation to the amounts of clay minerals present. During April 1974 the maximum concentration of biogenous Si rather than occurring in surface waters, is well developed at 25 m. Its areal trend here in contrast to the more constant Si/Al ratios clearly increases westwards. Further, the upper 50 m of water contains much greater concentrations of biogenous Si than the underlying waters. This is most evident when seasonal changes in biogenous Si are examined (Figure 4). The results show that a

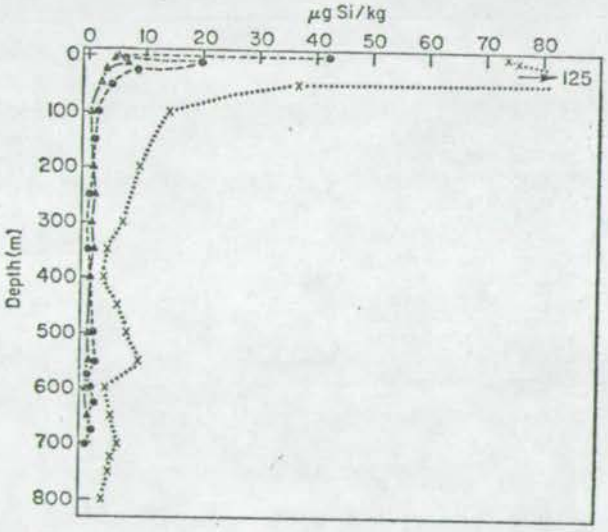


Figure 4. Seasonal change in concentrations of particulate biogenous Si (µg/kg) in the inner part of Hardangerfjorden, Norway. – – ● – – ● – –, H35 (August 1972); —▲—▲—, H65 (October 1973); · · · × · · · × · · ·, H70 (April 1974).

considerable standing crop exists during April 1974 with biogenous Si concentrations approximately an order of magnitude more abundant than at other times. Microscopic examination shows that diatoms are plentiful in these horizons. During summer (H35) maximum biogenous Si concentrations seem to occur in surface waters while in early autumn (October, H65) there is little siliceous skeletal matter. In the deeper waters biogenous Si is also higher in spring than at other times, especially between 400 m and 550 m where anomalously high Ti/Al ratios exist. This feature is clearly seen in the inner station (H70) and to a lesser degree in H35 and can be interpreted as due either to an unusual concentration of plankton which has been observed at this time of the year at the same locality and in similar water depths (Lie, 1967), or to plankton remains.

Aluminosilicates derived from a terrain of acid gneisses and siliceous sediments are generally low in Ca. Hence, particulate Ca concentrations (Table 1) are due largely to the presence of biogenous carbonate. Surface and near surface Ca concentrations are considerably higher than at depth especially where biogenous Si is also at a maximum, e.g. at 25-m depth (Stations H67, H68, H70). Although no linear correlation exists between these two constituents, in the surface water both increase westwards. The results of both areal and seasonal investigations clearly show that siliceous rather than calcareous organisms form the bulk of the standing crop in the upper waters. However, seasonal differences in biogenous Si concentrations, which may relate to changes in productivity, are not mirrored by the change in biogenous carbonate. For example, while biogenous Si is more concentrated in spring than at other times, particulate carbonate appears to be at least as abundant in the autumn (H65).

The increase of Ca in some near bottom waters, that is in station H68, follows particulate aluminosilicate concentrations and shows as well unusualy high Ca/Al ratios (0·4). This feature almost certainly implies resuspension of both particulate carbonate and terrigenous constituents. It is interesting to note that there is no corresponding defined increase in biogenic Si in these waters.

Some increase in particulate Ca is seen in the midwaters (400–550 m) of station H70, and broadly follows the pattern of high biogenous Si concentrations and Ti/Al ratios.

Distribution of Fe and Mn

In particulate matter iron is almost certainly partitioned between aluminosilicates and other constituents, notably oxides and Fe associated with organic matter (Spencer & Sachs, 1970; Price & Calvert, 1973). In previous publications some attempts have been made to see variations in non-silicate Fe from studies of the distribution of 'excess' Fe over that held in silicates (Spencer & Sachs, 1970; Price & Calvert, 1973; Price, 1974*a*), based on an adopted but arbitary Fe/Al ratio for aluminosilicates. The value of this ratio has been quoted between 0·5–0·7. However, because of considerable areal and seasonal variations in the amount of particulate matter in Hardangerfjorden and the lack of an accurate knowledge of the Fe/Al ratio of silicates, to adopt a specific value for this ratio may produce erroneous results and conclusions. Instead, variations in the Fe/Al for total particulate matter are quoted in Table 2. However, as the mean Fe/Al ratio for particulate matter in river waters entering Hardangerfjorden is close to unity (Table 2), deviations in Fe/Al ratios from this value, in respect of the particulate matter in the fjord, provide some general guide to changes in the amount of non-silicate particulate Fe in the waters.

The Fe/Al ratio of particulate matter in the upper waters do not show any obvious areal or seasonal change. However, for the water column as a whole, Fe/Al ratios are substantially higher below 600 m. This particularly applies in the case of samples collected from the inner basin (H35, H65 and H70). There is no obvious increase in Fe/Al ratios in the surface waters as found in other studies (Price & Calvert, 1973; Price, 1974*b*) where Fe oxide or biogenous matter containing Fe is thought to occur.

Unlike Fe, nearly all the particulate Mn is likely to be confined to non-silicate constituents as sediments (e.g. shales) display very low Mn/Al ratios (e.g. 0·01, Krauskopf, 1965). Hence, we attribute the total particulate Mn (Tables 1 and 3) to non-silicate Mn. The concentration of Mn in the upper water (<25 m) is considerably greater than those situated immediately below. Moreover, higher concentrations are seen in spring in the inner parts of the fjord (H70) than elsewhere (H67, H68). This is even more obvious when the Mn concentrations of unwashed filters are examined (see Table 3).

TABLE 3. Concentrations of Mn and P (µg/kg) in unwashed and Zn and Pb (µg/kg) in unwashed and washed particulate matter from Hardangerfjorden, Norway

Depth (m)	Mn	ΔMn	% rem.	P	ΔP	% rem.	Zn unwashed	Zn washed	% rrem.	Pb unwashed	Pb washed	% rem.
Station H70												
0	2·98	2·54	85	11·95	9·15	71	2·4	0·5	79	2·0	0·6	70
5	2·57	1·46	57	10·33	6·65	64	1·6	0·8	50	1·2	0·5	58
25	2·24	1·38	62	11·47	7·79	68	2·1	1·3	38	1·2	0·6	50
50	1·64	1·11	68	2·19	1·39	63	0·6	0·1	83	1·8	0·5	72
100	0·47	0·26	55	0·98	0·54	55	0·3	0·1	67	0·7	0·2	71
200	0·55	0·30	55	0·68	0·27	40	<0·1	<0·1	—	0·2	0·2	0
300	0·64	0·30	47	0·63	0·28	44	0·1	<0·1	—	0·4	0·2	50
350	0·49	0·14	29	0·49	0·14	29	0·4	0·1	75	0·4	0·1	75
400	0·49	0·26	53	0·36	0·16	44	0·1	<0·1	—	0·3	0·1	67
450	1·15	—	—	0·60	—	—	0·2	—	—	0·3	—	—
500	1·35	0·66	51	0·62	0·25	40	0·2	<0·1	>50	0·6	0·1	83
550	1·48	0·63	43	0·72	0·25	35	0·1	<0·1	—	0·2	0·2	0
600	1·51	0·35	23	0·43	0·14	33	0·1	<0·1	—	0·3	0·1	67
650	2·00	0·44	22	0·50	0·21	42	0·2	<0·1	>50	0·4	0·2	50
700	1·32	0·45	34	0·59	0·20	34	0·2	<0·1	>50	0·3	0·1	67
725	3·32	0·68	20	0·47	0·13	28	0·2	<0·1	>50	0·2	0·2	0
750	5·33	0·68	13	0·59	0·18	31	0·4	0·2	50	0·5	0·2	60
825	6·59	1·31	20	0·49	0·08	16	0·3	<0·1	>67	0·3	0·2	33
Station H68												
0	1·25	1·12	90	5·17	3·12	60	1·0	0·5	50	0·9	0·4	56
5	1·03	0·84	82	4·11	2·35	57	0·8	0·3	63	1·1	<0·1	>91
10	1·20	0·68	57	4·86	2·38	49	0·9	0·8	11	0·9	0·2	78
25	1·90	1·07	56	13·77	7·40	54	3·0	2·3	23	1·3	0·4	69
50	0·69	0·42	61	2·09	1·30	62	0·3	0·2	33	0·8	<0·1	>88
100	0·29	0·12	41	0·64	0·31	48	0·1	<0·1	—	0·4	<0·1	>75
150	0·41	0·14	34	0·59	0·15	25	0·1	<0·1	—	0·5	<0·1	>80
200	0·37	0·09	24	0·29	0·07	24	0·1	<0·1	—	0·5	0·4	20
300	0·64	0·18	28	0·34	0·06	18	<0·1	<0·1	—	0·3	0·1	67
350	1·00	0·57	57	0·41	0·02	5	0·2	<0·1	>50	0·4	<0·1	>75
400	1·04	0·28	27	0·38	0·03	8	<0·1	<0·1	—	0·3	<0·1	>61
500	1·27	0·30	24	0·45	0·07	16	0·1	<0·1	—	0·6	<0·1	>83
550	0·97	0·41	42	0·35	0·11	31	<0·1	<0·1	—	0·2	0·2	0
600	1·87	0·31	17	0·60	0·09	15	0·1	<0·1	—	0·6	0·2	67
640	2·01	0·13	6	0·58	0·08	14	0·1	<0·1	—	0·4	0·2	50
Station H67												
0	0·29	0·21	72	2·45	1·52	62	0·4	0·3	25	1·0	<0·1	>90
5	1·11	0·72	65	9·06	5·71	63	1·8	1·0	44	1·7	0·3	82
10	0·64	0·27	37	8·61	5·40	63	0·7	0·3	57	1·6	0·4	75
25	1·59	1·15	72	25·50	18·06	71	4·4	2·4	45	1·6	0·4	75
50	0·50	0·27	54	1·33	0·33	25	0·2	<0·1	>50	0·6	0·2	67
100	0·41	0·10	24	0·94	0·39	41	0·2	<0·1	>50	0·6	0·2	67
150	0·42	0·12	29	0·61	0·26	43	<0·1	<0·1	—	0·6	0·2	67
200	0·43	0·19	44	0·50	0·16	32	0·1	<0·1	—	0·3	0·1	67
250	0·45	0·16	36	0·42	0·12	29	0·1	<0·1	—	0·6	<0·1	>83
300	0·62	0·33	53	0·85	0·20	24	<0·1	<0·1	—	0·7	0·1	86
350	1·03	0·26	25	0·50	0·15	30	0·1	<0·1	—	0·1	0·1	0
400	1·14	—	—	0·41	0·00	0	<0·1	—	—	0·7	—	—
425	1·54	0·05	3	0·57	0·11	19	<0·1	<0·1	—	0·4	<0·1	>75
475	1·30	0·13	10	0·48	0·10	21	<0·1	<0·1	—	0·5	<0·1	>80

ΔP and ΔMn represent the respective losses of these elements for unwashed and washed samples as given in Table 1. Analytical precision for Zn and Pb is 15%.

A more pronounced increase of Mn is seen in the deep waters where concentrations increase with depth to levels an order of magnitude higher than in the midwaters (Figure 5); an increase also occurs in Mn/Al ratios which may show values greater than unity. This increase in Mn in waters below 400–540 m is also apparent from the analyses of washed samples collected at different seasons (H35, H65, H70). These changes at depth and their relationship to other particulate constituents are discussed more fully below.

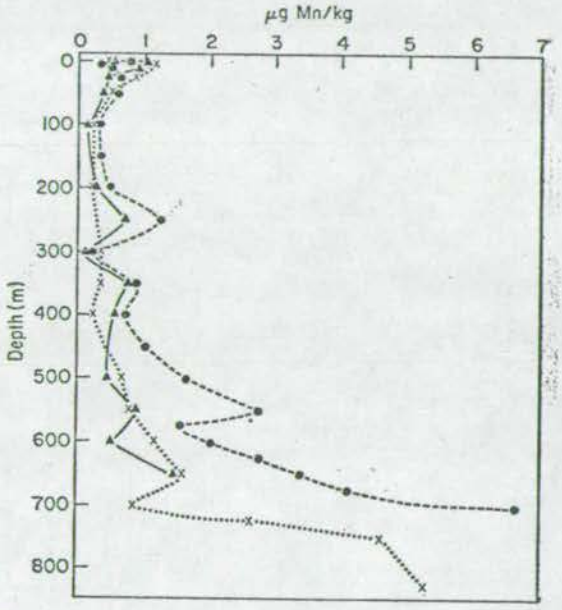


Figure 5. Profiles of particulate Mn (µg/kg) in samples analysed after washing in distilled water for the inner station of Hardangerfjorden, Norway, collected at different seasons. – – ● – – ● – –, H35 (August 1974); —▲—▲—, H65 (October 1973); · · · × · · · × · · ·, H70 (April 1974).

Particulate organic matter

Recent observations on variations in particulate P in marine waters have been used to describe change in particulate organic matter concentrations (Spencer & Sachs, 1970; Copin-Montegut & Copin-Montegut, 1972; Price, 1974*a*, *b*) on the assumption that little P is held in other constituents, except iron oxides (Price & Calvert, 1973; Price, 1974*a*) which are considered on the basis of low Fe/Al ratios, not likely to be plentiful in the waters of Hardangerfjorden.

The profiles of particulate P on unwashed material collected in April 1974 (H67, H68 and H70) (Table 3 and Figure 6) show clearly a seaward increase in P in the upper waters, especially at 25 m depth. Phosphorus concentrations at this depth are usually higher than those in surface waters. There is no obvious trend in particulate P variations in the deeper waters except in station H70 where there is a slight P increase between 400 m and 550m (Table 3, Figure 6). These trends parallel those of biogenous Si (Table 2). Seasonal variations in P on washed particulate matter (H35, H65, H70) (Table 1) are also consistent with the variations in productivity but are noticeably lower in their concentrations indicating some loss of phosphorus during the washing of dried samples.

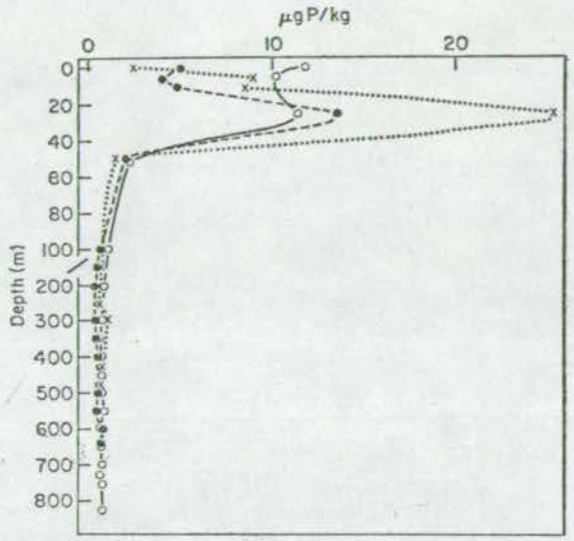


Figure 6. Areal variations of particulate P (µg/kg) on unwashed particulate matter samples for three stations in Hardangerfjorden, Norway, collected during April, 1974. Note change of depth scale at 100 m. ··· × ··· × ···, H67; – – ● – – ● – –, H68; —○—○—, H70.

Particulate S and Mg concentrations were only calculated on washed filters because of contributions from sea-salt sulphate and Mg in unwashed samples. As with particulate P the concentrations of S (Table 1) are likely to be held in organic matter (Price & Calvert, 1973). Its variation areally and seasonally closely follows P being enriched in the upper waters, particularly at 25 m depth (H67, H68, H70) during the spring and in the midwaters of H70 between 400 m and 550 m. While much of the Mg (Table 1) is likely to be held within silicates, which may vary compositionally in different waters as suggested above, the increase of Mg relative to Fe and the very high Mg/Al ratios in the uppermost 25 m of each profile, indicates, that a proportion of the total Mg content of the particulate matter may be bound in organic matter.

Both Zn and Pb are thought to be associated with organic matter as their abundances with respect to Al on unwashed samples exceed that observed in aluminosilicates by two orders of magnitude (Table 3). A similar argument can be made for much of the Mn in these upper waters (Table 3). In most surface waters Zn occurs in slightly higher concentrations than Pb with maximum values of 4·4 µg/l and 2·0 µg/l, respectively. The data in Table 3 show that this level of concentration occurs only in the uppermost 50 m of each profile and generally peaks at 25 m where particulate P, biogenic Si and Ca are also high. Below, there is a threefold decrease in Pb concentrations while Zn in the mid and deep waters is usually close to or below the limit of its analytical detection (0·1 µg/l). Close inspection of the Zn and Pb data and the levels of P and biogenic Si suggests that these metals more closely correlate with the particulate P of unwashed material than Si. Vinogradova & Kovalskiy (1962), Bowden (1966) and Martin & Knauer (1973) quote enrichments of either Zn or Pb or both elements in siliceous and non-siliceous organisms.

Element losses of biological constituents upon washing

As washing of the particulate matter in distilled water has a deleterious effect on the quality and chemistry of particulate organic substances, as noted above, data for P, Zn, Pb and Mn

for stations H67, H68 and H70 are quoted as concentration levels on unwashed (Table 3) as well as washed samples. Any loss of elements by this treatment implies breakdown and removal of constituents, especially organic substances. In the case of Al, Si, Ti and probably Fe too, no loss of element concentration occurred, indicating that they are firmly fixed in the non-organic constituents of the particulate matter. In this context it is interesting to note that differences in Ti/Al ratios of both washed and unwashed filters between the near surface, some midwaters (H70, 400–550 m) and the deep waters may indicate either some change in mineralogy of the terrigenous constituents or variation in the mode of fixation of Ti. Closer inspection of data from station H67, H68 and H70 (Table 1) suggests that while Ti concentrations are usually linked with aluminosilicates, this is not always the case. Price (1964*b*) has noted very high Ti concentrations relative to Al (Ti/Al $\sim$ 0·3) in surface waters over the East Pacific Rise and has attributed this trend to either uptake onto organic matter or more likely to incorporation into siliceous skeletal remains which are very abundant relative to aluminosilicates (e.g. Si/Al=50). In Hardangerfjorden it is not easy to demonstrate these relationships because skeletal Si is nearly always coincident with high concentrations of aluminosilicates. Further, the presence of high concentrations of Al, especially in relation to the amounts of Al in ocean particulate matter, tends to mask changes in Ti/Al ratios caused by contributions from sources other than aluminosilicates.

Results of analysis of particulate P before and after washing show very considerable differences for nearly all samples (Table 3). In surface and near surface waters (<25 m) this loss of P (ΔP) represents some 50–70% of the original P concentrations; at depth the percentage loss is considerably less (0–30%) but is somewhat higher in station H70 than H67 and H68. It would appear that degradation of organic P, presumably helped by microbiological agents, took place during and after the drying of the samples. It is not known what effects would have taken place had the particulate matter been washed immediately after collection.

This behaviour of particulate P between the upper and lower waters suggests some variation in the quality of the organic matter, that is, in the deep waters it appears more refractory than that occurring at shallow depths. Data on the disribution of particulate P in relation to other organic constituents is scarce. Menzel & Ryther (1964) found essentially no phosphorus in deep water particulate matter. Holm-Hansen *et al.* (1966) found that the C/P ratios of particulate matter changed with depth in the waters off California and suggested that much of the P in deep waters occurs as nucleic acid. The conclusion reached by Riley (1970) is that deep-water particulate matter is poor in P compared with plankton because much of the P in living organisms is regenerated quickly after their death. If we assume that the degradation of organic matter induced by the drying and storage of the samples follows the same general pathway of decomposition of plankton seston under marine conditions the evidence presented in Table 3 for the upper and lower waters supports the concept of a rapid release of P from plankton in sea water.

Table 3 also shows concentrations of particulate Zn and Pb in different waters, analysed before and after treatment. In the upper waters the percentage losses of Zn and Pb approximate to that seen by particulate P, that is 40–60% and 50–90%, respectively. However, because of the low levels of concentration of both elements in the deeper waters, it is not possible to assess the change in concentrations with the same reliability as in the upper waters. However, percentage losses of Zn and Pb at depth do appear to be similar to those seen in the shallow waters.

If we confine our attention to the concentration losses of Zn and Pb to the upper waters, they do not appear to be strongly correlated with the amounts of P lost by the same treatment.

Rather, *total* zinc and lead concentrations relate more to the loss of P (ΔP). This is illustrated in Figure 7 for Zn and ΔP in the three profiles studied during spring. The ratio of total Zn concentration to ΔP for samples in the uppermost 25 m of water varies between 0·24 and 0·415, but shows no systematic areal or depth trend.

Manganese also shows a marked change in concentration before and after washing. This is most noticeable in the upper 25 m of water where 60–90% of Mn is lost (Table 3). At depth the difference is considerably less and percentage wise becomes quite small in bottom waters (~20%) where total Mn concentrations are high. At station H70, between 400–550 m, the loss percentage as well as Mn is higher (Table 3) and conforms to the pattern of higher particulate P and other elements.

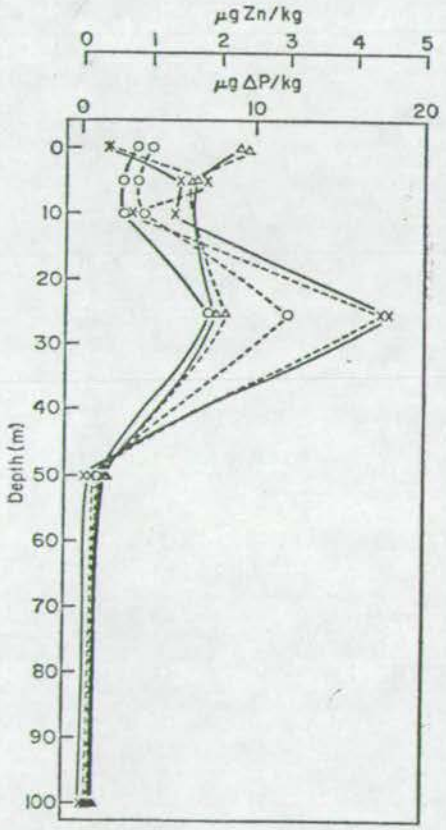


Figure 7. Changes in concentration of Zn (μg/kg) on unwashed particulate matter and the loss of P upon washing (ΔP) of samples collected in April, 1974 in the upper 100 m of water from Hardangerfjorden, Norway. H67: —×—×—, ΔP; – – × – – × – –, Zn. H68: —O—O—, ΔP; – – O – – O – –, Zn. H70: —△—△—, ΔP; – – △ – – △ – –, Zn.

Geochemistry of particulate matter in the bottom waters

Terrigenous element concentrations as denoted by Al and Ti usually show an increase in deeper waters where bottom sediment resuspension occurs. For instance, sediment resuspension in the Gulf of Maine (Spencer & Sachs, 1970) can cause a 50-fold increase in particulate Al concentrations with respect to surface waters. Similar trends have also been

noted by Price & Calvert (1973) in coastal waters. Only in station H68 and to a lesser extent H70 is there any clear evidence of some increase in terrigenous constituents in the bottom waters (Table 1) lying 30–40 m above the bottom sediment. It is evident that if we also consider the other stations, bottom sediment resuspension of terrigenous and biogenous constituents is small or non-existent. It would appear therefore that bottom flushing is not a recent event with respect to the times of sampling. Nevertheless, the high dissolved O_2 contents of the bottom waters imply that bottom water renewal is a frequent mechanism.

In contrast to the distribution of terrigenous constituents, total particulate Mn and Mn/Al ratios, show a remarkably high and increasing concentration at all stations below about 400 m (Tables 1 and 3, Figure 5). The position of the initial increase in Mn concentration appears to deepen eastwards and occurs at 450 m in the inner basin. At depth, little Mn is removed by washing compared with that observed and thought to be organic Mn in surface waters (Figure 8). Because of its high concentrations with respect to elements associated with organic matter, we assume that the bulk of the deep water Mn is inorganic and probably occurs as oxide. Non-silicate iron, denoted by Fe/Al ratios (Table 2), may also occur in the bottom waters and is similarly interpreted as iron oxides. However, it is not possible to correlate the amounts of dispersed Mn and Fe because of difficulties in assessing the specific amount of non-silicate Fe in samples as we have discussed above.

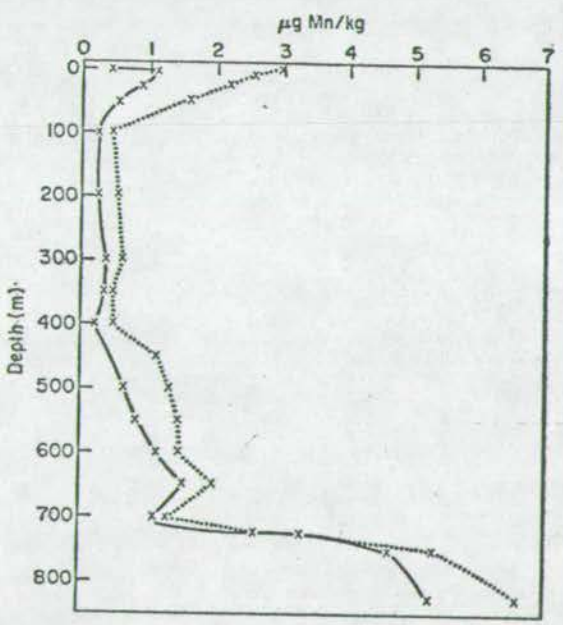


Figure 8. Concentrations of Mn (µg/kg) in particulate matter representing both unwashed and washed samples from Station H70 in Hardangerfjorden, Norway. – – × – – × – –, unwashed samples; —×—×—, washed samples.

A feature noted by us in neighbouring fjords is that the increasing trend of Mn concentrations with depth is interrupted by a decrease at a specific depth above the seabed. In stations H35, H65 and H70 this decrease occurs at ~ 160 m (Figure 5). Any attempt to understand the source and mechanism of emplacement of Mn in the lower waters must consider this feature and the others described above.

High particulate Mn concentrations are known in certain waters of restricted basins and occur as a result of redox changes and a mechanism involving both advection and diffusion of Mn about a redox boundary either in the water or at the sediment–water interface (Spencer *et al.*, 1972; Price, 1974*a*; Price & Calvert, 1973).

The chemical characters of the waters and sediments of Hardangerfjorden nowhere conforms to these conditions. It shows high dissolved O_2 contents at all water depths (Figure 3). Also, the surface sediments are thoroughly oxic in character and while some redistribution of Mn may occur from diagenesis through burial, any upward migration of Mn by this process is much more likely to be reoxidized and reprecipitated in the surface sediments, or even below it, than be released into the overlying water. The extent of particulate Mn enrichment in the waters of the fjord is also very different to that seen in restricted basins. Although it may be largely a feature of the intensity of density stratification in the water, Mn anomalies are not seen more than a few tens of metres above its redox boundary in restricted basins. In Hardangerfjorden particulate Mn enrichment extends ~400 above the sediment. Moreover, within restricted basins dissolved Mn (II) concentrations in bottom waters are much greater (Price & Calvert, 1973) than observed in Hardangerfjorden (0·1–0·5 µg/kg). It would appear that little particulate Mn in the fjord results from a *direct* release of Mn^{2+} from bottom waters. Instead, we believe that the enrichment of particulate Mn is the result of resuspension of bottom sediment during periods of flushing or similar disturbances, even though the composition of the particulate matter is quite dissimilar from that of bottom sediments. Mn constitutes about 20–30 % of the inorganic elements in the particulate matter in contrast to that measured in the surface sediments (0–2 cm), i.e. 0·15–0·25 %.

Alternative mechanisms of sediment resuspension must be considered in evaluating these trends of particulate Mn and other constituents. It is possible that preferential resuspension of particulate Mn and aluminosilicates occurs during periods of bottom water disturbances. However, to our knowledge, preferential resuspension of one component to the almost exclusion of others has never been demonstrated. Furthermore, the particulate matter in the lower waters does not appear to have been recently introduced by flushing. With such an event the displacing water would have properties similar to surface waters, that is it should display concentrations of elements commensurate with that seen in particulate organic matter and biogenic components. Instead, particulate matter occurring between 400 m and 550 m in spring (H70) rather than the bottom waters appears to have most of these properties. It has higher particulate P, leachable P and Mn, biogenous Si and Ti/Al ratios and appears to have been recently introduced into the inner parts of the fjord. It is more probable that the features of high particulate Mn and low aluminosilicates in the deep waters represent the residuum of a previous bottom water flushing which caused resuspension of both sediment Mn and aluminosilicates. Resettling of coarser grained aluminosilicates occurred, leaving the remaining particulate matter enriched in Mn to appear as a quasi-conservative property of the lower waters. The profiles of Mn below 400–450 m showing an interrupted trend of increasing Mn with depth, as described above, suggest that two periods of bottom water flushing have occurred in the past. The latter caused renewal of the deepest 160 m of water and displaced water from an earlier event which is represented by the upper portion of the Mn anomaly.

General discussion

Concentration patterns of inorganic particulate matter, especially aluminosilicates in the upper waters of fjords as described above, appear to be related to season and in particular to

the development of the pycnocline. During periods of high runoff (H35) as occurs in summer, most of the inorganic particulate matter resides in the surface waters. The marked change in concentration of aluminosilicates above the pycnocline, in contrast to that seen below, indicates that intense density stratification in the surface waters provides an effective barrier to particle settling. During periods of low runoff (spring, H70) when the near surface pycnocline is virtually absent, concentrations of surface particulate matter are lower. Under these circumstances highest levels of inorganic particulate matter reside in waters containing maximum concentrations of organic P and skeletal constituents. It is possible that this occurrence of high concentrations of biogenous matter and aluminosilicates at a specific level, for example 25 m, may be coincidental. However, as there is little evidence of any density stratification at this depth, it would seem that the inorganic and biogenic constituents are intimately associated. This association appears to effectively prevent fallout of particulate aluminosilicates from the near surface waters. The occurrence of inorganic substances and organic aggregates as particulate matter has been known for some time and may be the result either of adsorption of ions or scavenging of solid materials (Riley, 1970). The intimate association of particulate Al and organic P implies some attachment of aluminosilicates to microplankton or its debris. However, little information is available on the amount and type of aluminosilicates that can be held in this way.

Little is known on the sorption of ions onto deep water particulate matter, although organic aggregates in deep waters can contain manganous ion in small concentrations (0·01–0·06 µg/l; Wangersky & Gordon, 1965). More information has been accumulated for the trace element assemblages of various groups of plankton (Bowen, 1966; Martin & Knauer, 1973). Martin & Knauer attempted to assess the patterns and types of association of trace elements in plankton believing that many elements are held by adsorption and by the development of hydroxy complexes as well as being possibly associated with inorganic particulate matter. In nearly all cases they show that Zn preponderates over Pb as observed in the organic matter of upper waters of Hardangerfjorden.

While the concentrations of particulate Zn, Pb and Mn appear to be associated with organic matter, it is not known if these metals reside at the surface or are incorporated within the organisms. Certainly, their losses during drying and washing contrast to that of Ti which is thought to accumulate in skeletal remains. However, the reason for the interrrelationship of total Zn before treatment with the loss of P (ΔP) from the organic matter is unclear. The removal of a considerable proportion of Zn in the organic matter of the deeper waters may imply surface sorption effects. The same may be true for much of the Mn lost in washing.

It has been suggested that the release of phosphorus from plankton upon death and its regeneration into new organisms is rapid (Riley, 1970; Stumm & Morgan, 1970). As Zn, Pb and Mn are in some way associated with the release of P from organisms, we consider that release and regeneration of these and probably other metals will also be rapid. The result of these processes will be a recycling of much of the trace metals within the euphotic layer of marine waters and only a small proportion of the constituent elements of plankton will be transported through this layer towards the seafloor.

Within stratified estuaries, especially fjords, displaying strong inward moving compensating currents to counteract surface flow, it is possible that release of organic elements there will be transported towards the head of a fjord. The landward increase of dissolved P in compensating currents (Stumm & Morgan, 1970) has been attributed to this mechanism.

The presence of Mn in bottom water nepheloid layers is important especially in relation to the sedimentation of Mn in oceans. It would appear that bottom water nepheloid layers can either contain high aluminosilicate (or biogenous) concentrations with very subordinate

Mn oxides or display compositions where Mn is abundant. Following the observations made in this study, it is possible to assess the extent of recent or more correctly contemporary bottom sediment disturbances by studying the amounts of resuspended aluminosilicates (or biogenous matter) in the bottom waters. In addition, it would seem that the relative amounts of Mn to aluminosilicates etc. compared with that of bottom sediments can provide some estimates of the time delay between resuspension and sampling; higher Mn indicating a greater lapse of time. It follows from this that studies comparing the composition of the nepheloid layer and the sediments with regard to Mn are irrelevant when attempts are being made to understand its origin in sediments.

Acknowledgements

We wish to thank Hans Holtedahl (University of Bergen) for his encouragement and support during this study and providing the R/V Hans Reusch for work in Hardangerfjorden. K. Sögnen provided valuable help during the field work and G. Angell assisted in the chemical analysis. H. Svendsen provided us with dissolved oxygen values for 1972.

The work was supported by grants from the National Environment Research Council (Great Britain) and Norges Almenvitenskaplige Forskningsråd (D.41.31–18).

References

Bowen, H. J. M. 1966 *Trace Elements in Biochemistry*. Academic Press, London and New York, 271 pp.

Copin-Montegut, C. & Copin-Montegut, G. 1972 Chemical analyses of suspended particulate matter in the north-east Atlantic. *Deep-Sea Research* **19**, 445–452.

Feely, R. A., Sackett, W. M. & Harris, J. E. 1971 Distribution of particulate aluminium in the Gulf of Mexico. *Journal of Geophysical Research* **76**, 5893–5902.

Gade, H. 1973 *Oceanografiske Observasjoner i Fensfjorden* 1972. (A report to Norsk Hydro, 12 pp.)

Goldschmidt, V. M. 1954. *Geochemistry* 730 pp. (Muir, A., ed.) Oxford University Press, Oxford.

Haakstad, M. 1970 Cand. real Thesis, University of Oslo.

Holm-Hansen, O., Strickland, J. D. H. & Williams, P. H. 1966 A detailed analysis of biologically important substances in a profile off Southern California. *Limnology and Oceanography* **11**, 458–561.

Holtedahl, H. 1965 Recent turbidites in the Hardangerfjord, Norway. *Proceedings of the 17th Symposium, Colston Research Society, Bristol, U.K.* 35 pp.

Krauskopf, K. B. 1965 *Introduction to Geochemistry* 721 pp. McGraw-Hill, New York.

Lie, U. 1967 The natural history of the Hardangerfjord. 8. Quantity and composition of the zooplankton, September 1955–September 1956. *Sarsia* **30**, 49–74.

Martin, J. H. & Knauer, G. A. 1973 The elemental composition of plankton. *Geochimica et Cosmochimica Acta* **37**, 1639–1653.

Menzel, D. W. & Ryther, J. H. 1964 The composition of particulate organic matter in the western North Atlantic. *Limnology and Oceanography* **9**, 179–186.

Pichard, G. L. 1961 Oceanographic features of inlets in the British Columbia mainland coast. *Journal of the Fisheries Research Board of Canada* **18**, 907–999.

Pickard, G. L. 1970 Some physical oceanographic features of inlets of Chile. *Journal of the Fisheries Research Board of Canada* **28**, 1077–1106.

Price, N. B. 1974*a* Major element composition of suspended particulate matter in the waters of the Cariaco Trench, Venezuela. *Deep-Sea Research* In the press.

Price, N. B. 1974*b* The composition of suspended particulate matter in waters over the East Pacific Rise. *Marine Chemistry* In the press.

Price, N. B. & Calvert, S. E. 1973 A study of the geochemistry of suspended particulate matter in coastal waters. *Marine Chemistry* **1**, 169–189.

Riley, G. A. 1970 Particulate organic matter in sea water. *Advances in Marine Biology* **8**, 1–118.

Saelen, O. H. 1962 The natural history of the Hardangerfjord. 3. The hydrographical observations 1953–56. Tables of observations and longitudinal sections. *Sarsia* **6**, 1–25.

Saelen, O. H. 1967 Some features of the hydrography of Norwegian fjords. In *Estuaries* pp. 63–70 (Lauff, G. H., ed.) American Association for the Advancement for Science Publication No. 83.

Spencer, D. W., Brewer, P. G. & Sachs, P. L. 1972 Aspects of the distributions and trace element composition of suspended matter in the Black Sea. *Geochimica et Cosmochimica Acta* **36**, 71–86.

Spencer, D. W. & Sachs, P. L. 1970 Some aspects of the distribution, chemistry and mineralogy of suspended matter in the Gulf of Maine. *Marine Geology* **9,** 117–136.

Ström, K. M. 1936 Land-locked waters. Hydrography and bottom deposits in badly-ventilated Norwegian fjords, with remarks upon sedimentation under aneorobic conditions. *Norske Videnskaplige Akademiske Skrifter, Oslo* **1,** 1–85.

Stumm, W. & Morgan, J. J. 1970 *Aquatic Chemistry* 583 pp. Wiley-Interscience, New York, N.Y.

Svendsen, H. 1973 *Oceanografiske undersökelser i Sörfjorden* 1972 (a report to the Environmental Committee of Odda, 17 pp.)

Taylor, J. H. 1974 Ph.D. Thesis, University of Edinburgh, 138 pp.

Thompson, T. G. & Barkey, K. T. 1938 Observations on fjord-waters. *Transactions of the American Geophysical Union* **19,** 257–260.

Vinogradova, Z. A. & Kovalskiy, V. V. 1962 Elemental composition of the Black Sea plankton. *Doklady of the Academy of Sciences of the U.S.S.R.* **147,** 217–219.

Wangersky, P. J. & Gordon, P. C. 1965 Particulate carbonate, organic carbon and Mn^{2+} in the open ocean. *Limnology and Oceanography* **10,** 544–550.

THE DISTRIBUTION OF HEAVY METALS IN SEDIMENTS OF SÖRFJORD, WEST NORWAY

J. M. SKEI, N. B. PRICE and S. E. CALVERT
Grant Institute of Geology, University of Edinburgh, Great Britain

and

H. HOLTEDAHL
Geologisk. Institut, Universitetet i Bergen, Norway

(Received 15 May, 1972)

Abstract. The bottom sediments of Sörfjord, West Norway, contain unusually high concentrations of Ag, Ba, Bi, Cd, Cu, In, Pb, Sb, Sn, and Zn. The concentrations of Zn and Pb reach ~ 10% by weight in some sediments. The concentrations of most of the elements are positively correlated, those of Pb, Cd, and Cu with Zn being particularly well developed; correlations also exist between Sb and Zn, and Ag and Cu. The concentrations of the metals in the bottom sediments decrease southwards and northwards from a locality close to a source of industrial waste.

1. Introduction

In the last two decades contamination by metals in marine and non-marine environments has attracted considerable attention. Following the disaster in Minimata Bay, Japan (Irukayma *et al.*, 1961) the efforts leading to the understanding of the cycling of certain contaminating metals in aqueous and biological systems have intensified (Jernlöv and Lann, 1971). Such studies have tended to center on the behavior of Hg and Cd (Haya *et al.*, 1963; Mullin and Riley, 1956). However while harmful effects by other metals are known, their toxicity to biological systems is less certain (Jones, 1938).

Most investigations concern the level of metals in inorganic and organic form in water and their consequent uptake by certain organisms. Considerably less attention has been paid to contaminating metals in bottom sediments, and little is known of their chemical behavior there, or their uptake by the benthos.

This paper reports an examination of the sediments of Sörfjord in West Norway into which many industrial effluents enter. It is hoped to show from the levels and distribution of heavy metals in the bottom sediments the extent of contamination about the source or sources of industrial wastes.

2. Location

Sörfjord is a north-south trending extension of Hardangerfjord, 1 to 2 km wide and 40 km long (Figure 1). The fjord has a step-like but generally flat bottom with a maximum depth of 390 m, shallowing towards the south towards Odda, where the water is approximately 50 m deep. Most of the run off enters the fjord close to Odda

Water, Air, and Soil Pollution **1** (1972) 452–461.

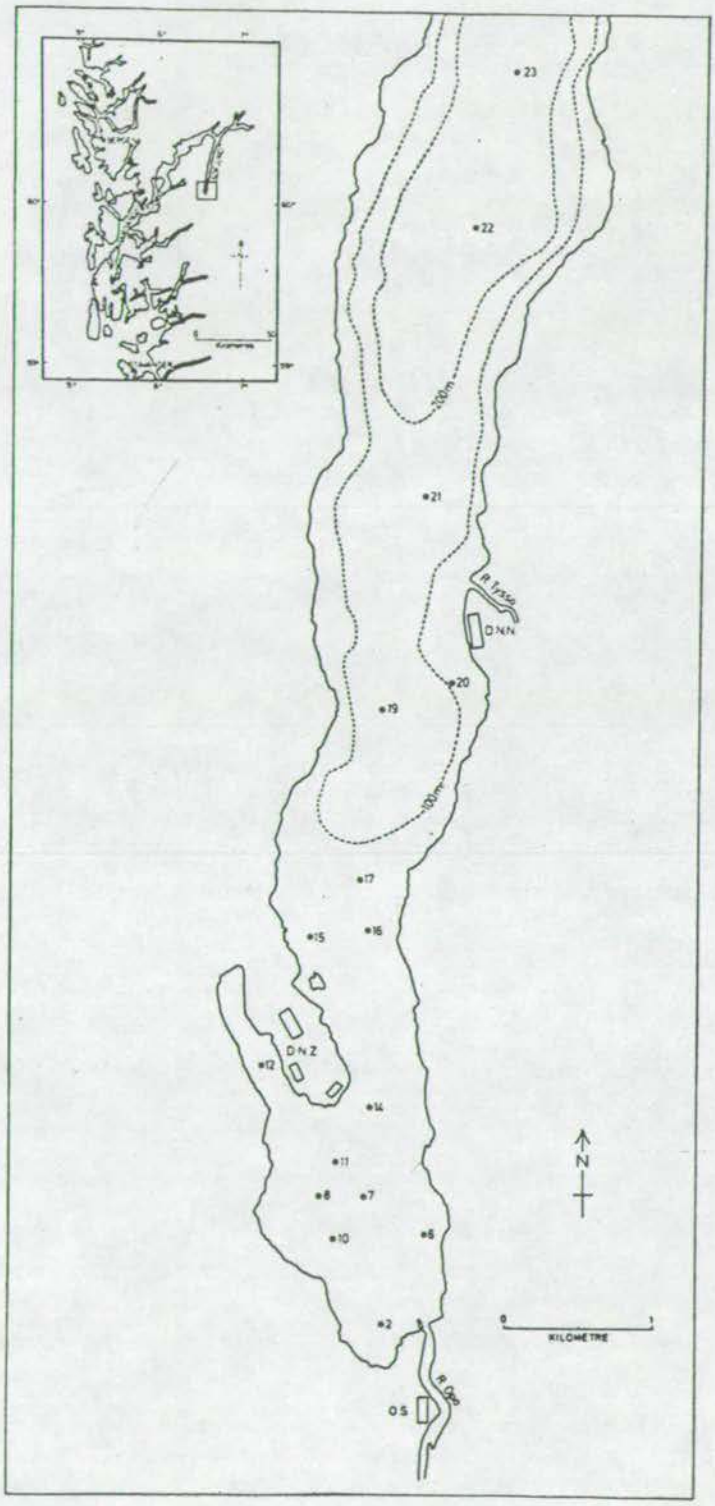


Fig. 1. Location of Sörfjord showing position of industrial sites.

via the River Opo while smaller amounts are supplied from the sides, especially from the west where streams drain the Folgefommi glacier.

Circulation in the fjord is estuarine. Salinity values of the surface 3 m of water are generally low (<15‰), increasing with depth to 35‰. These values are similar to those found in Hardangerfjord (Saelem, 1967).

Three industrial plants are situated about Odda (Figure 1) producing a variety of products (Table I). Industrial waste as solids and solutions is currently led into the fjord at depths of 0 to 25 m; daily amounts of various metals discharged are shown in Table II. The history of smelting extends some 50 yr; that of the other industries is less. There is no evidence that the type and composition of effluents have remained constant with time.

TABLE I

Types of production

Industry	Products
D.N.Z.	Zn, AlF_3, H_3PO_4
D.N.N.	Al
O.S.	$Ca(CN)_2$, $H_4C_2N_4$, CaC_2

(See Figure 1 for locations)

TABLE II

Discharge of metals in waste from industry about Odda
(kg day^{-1})

Element	Amount	Soluble/insoluble
Pb	4500	solid
Zn	6000	soluble/solid
Cu	300	solid
Cd	30	solid
Ag	30	solid
Hg	3	solid

3. Sampling and Analysis

Sediment cores, sampled with a 6 cm diameter gravity corer, were collected from 16 stations in the southern parts of Sörfjord. Most cores, especially those collected from the extreme south have at their surfaces a distinct layer of red to yellow-brown sediment. Below, the sediment is mid-grey in color, this being the same as surface sediments found in the northern parts of the fjord. The thickness of the red layer is variable and reaches a maximum of 11 cm at station 12. It thins northwards to 3 cm at station 21, and in the most northern station shown (Figure 1) the red color is not discernible.

Immediately after collection the sediment cores were frozen and surface 2 cm sections were sampled, dried, and ground for chemical analysis.

The concentrations of Ag, Ba, Bi, Cd, Cu, In, Pb, Sb, Sn, and Zn in the surface

sediments were determined by X-ray fluorescence analysis, using a tungsten anode, a LiF analysing crystal and a scintillation detector. The method used was similar to that of Reynolds (1963) where mass absorption differences in samples and standards were assessed by measuring variation in the Compton scatter intensity of a Mo Kα radiation source. Internationally accepted rock standards and synthetic standards mixed with a series of highly variable matrices (e.g. Fe_2O_3 5 to 50%) were used. Working curves were linear, and the precision of analysis was ±5% of the values recorded for most elements.

4. Results

The analyses of the surface sediments of Sörfjord are shown in Table III. These values can be better assessed when they are compared with metal concentrations in sediments accumulating in uncontaminated environments. Although the latter do show variations, it can be seen that the Sörfjord sediments have metal contents which are sometimes several orders of magnitude higher. This is most clearly seen with Zn and Pb where maximal values of 11.8% and 7.0% respectively are found and might be present as undiluted solid waste.

The metal contents are generally interrelated; those of Pb, Cu, Cd to Zn (Figures 2, 3 and 4) are particularly well defined. Good positive correlations also exist between Sb–Zn (Figure 5) and Ag–Cu (Figure 6). Contributions of the same elements made by that fraction of the surface sediments coming from natural sources are small. If we assume that the natural sediment contains 100 ppm Zn (Table IV) the intercepts of the above graphs indicate that this fraction of the sediment contains only 60 ppm Pb, 30 ppm Cu, and 2 ppm Cd.

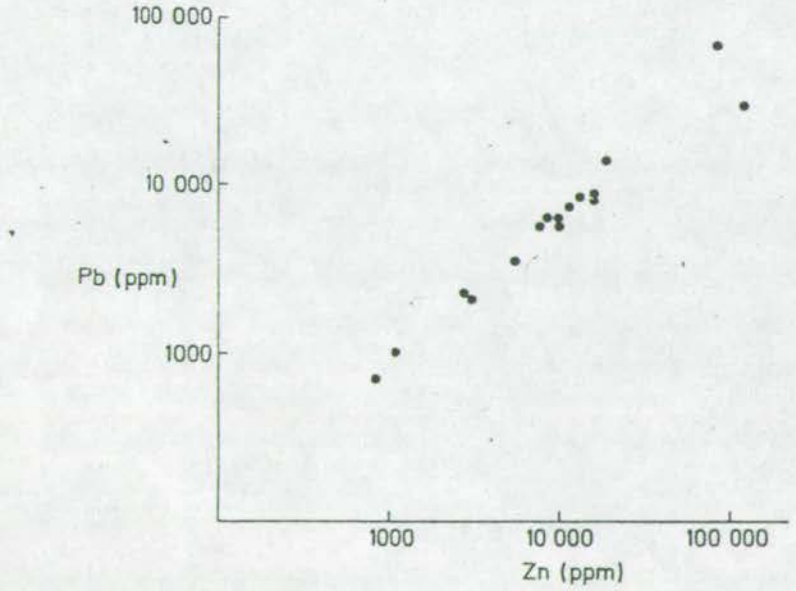


Fig. 2. Correlation of Pb and Zn in surface sediments of Sörfjord.

TABLE III

Chemical analysis of surface sediments from Sörfjord

Station No.	Ba	Sb	Cd	Pb	Zn	Cu	Sn	In	Ag	Bi
S12	6500	1080	850	30500	118000	12000	1350	81	190	3
S 7	480	280	61	6430	8300	970	390	8	42	21
S19	680	229	50	5800	7600	1040	265	14	35	17
S 6	580	103	32	2100	3000	450	118	4	19	23
S22	503	36	17	720	830	210	23	B.D.	16	20
S14	760	970	105	14300	17000	1920	1600	14	64	4
S20	443	147	50	5900	9800	1520	81	15	36	20
S10	600	90	74	8600	12950	2000	110	21	45	4
S11	778	270	84	8700	15800	2230	180	28	44	7
S15	950	150	54	6200	9850	1400	29	22	27	17
S 8	761	235	64	7500	11100	1600	218	21	42	11
S16	10500	760	330	70000	81000	10000	210	140	112	B.D.
S23	600	10	16	1030	1080	240	15	B.D.	13	23
S21	660	128	39	3600	5400	700	142	9	19	18
S 2	343	53	27	2250	2750	510	19	B.D.	19	16
S17	741	223	80	8250	15800	2000	110	22	35	12
Total range	343–10500	10–1080	16–850	720–70000	830–118000	210–12000	15–1600	B.D.–140	13–190	B.D.–23

B.D.: Below detection.

The extent of metal contamination of the surface sediments is clearly seen from the distribution of metals along a longitudinal section of the fjord (Figure 7). Most elements decrease in concentration both southwards towards Odda and northwards from station 16, which is close to the source of effluents from a Zn smelting plant (D.N.Z. Figure 1). It is probable that the fall off in element concentrations away from

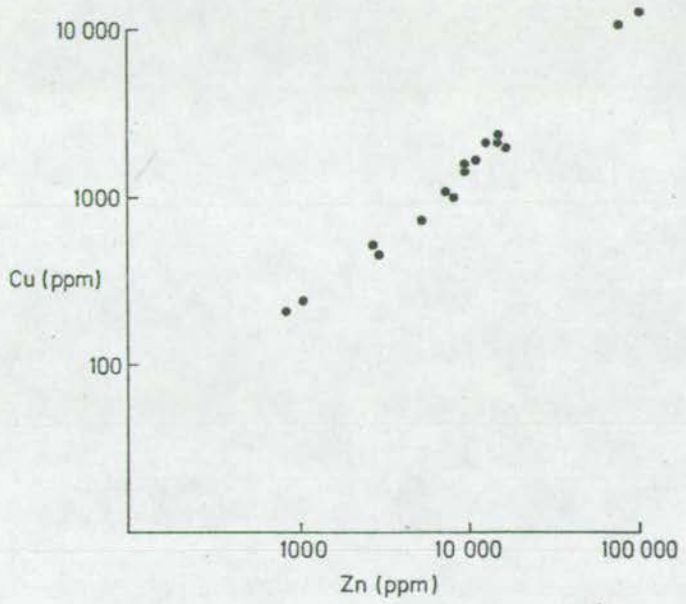


Fig. 3. Correlation of Cu and Zn in surface sediments of Sörfjord.

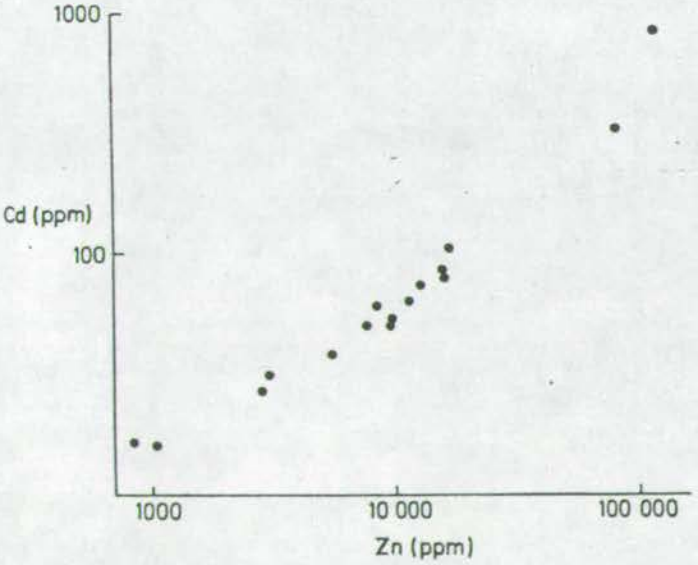


Fig. 4. Correlation of Cd and Zn in surface sediments of Sörfjord.

this station is a result of dilution by metal-poor natural sediment. However, at a distance of 10 km from D.N.Z., although the surface sediments are visually indistinguishable from natural sediments, their metal levels are far higher. Clearly the full extent of metal contamination in the sediments of the fjord is considerably greater than that shown here.

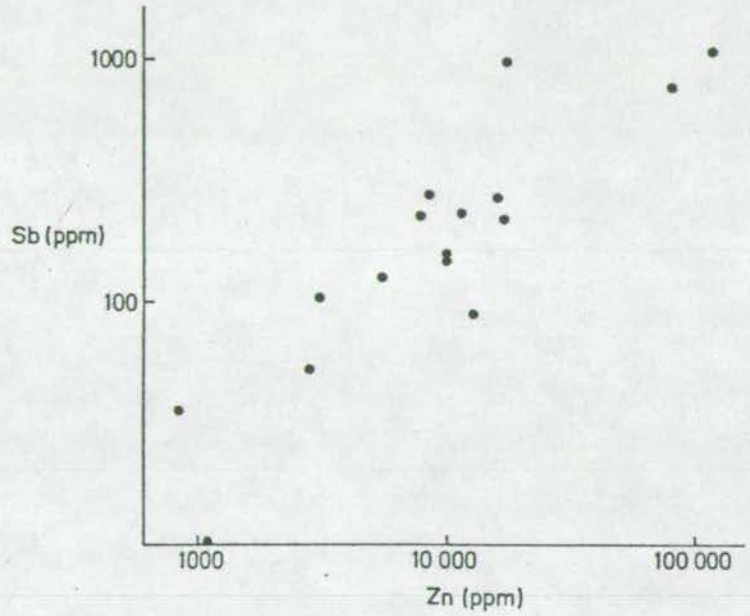


Fig. 5. Correlation of Sb and Zn in surface sediments of Sörfjord.

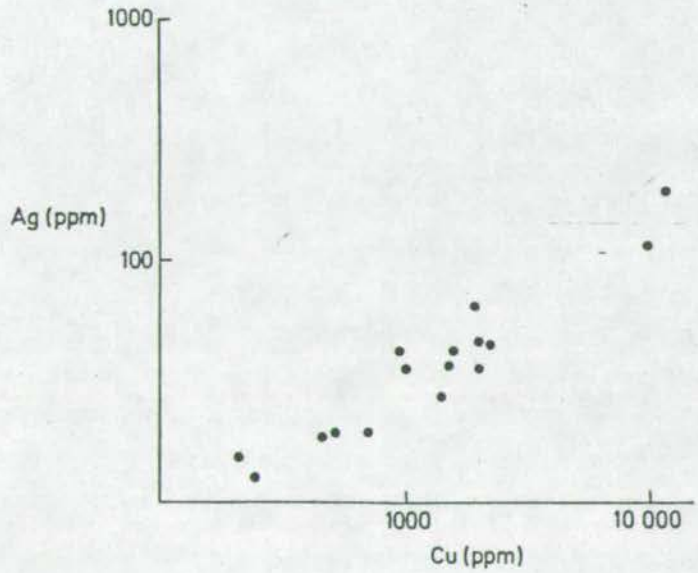


Fig. 6. Correlation of Ag and Cu in surface sediments of Sörfjord.

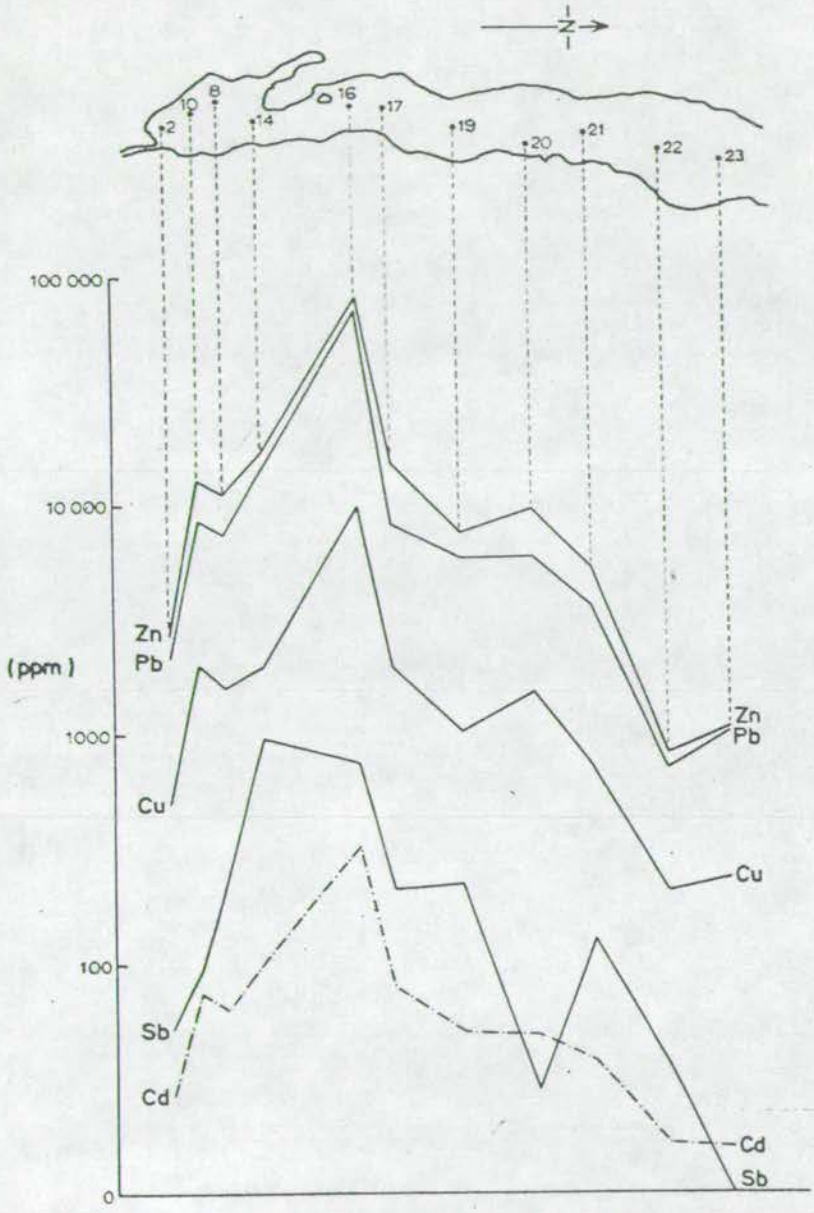


Fig. 7. Distribution of metals in the surface sediments on a longitudinal profile of Sörfjord, W. Norway.

The distribution of Bi is different from the other elements; it shows an increase in concentration away from station 16. Moreover, measurements of Bi in vertical profiles of some cores show higher values in the immediate sub-surface samples rather than at the surface. In view of the high Bi values compared with that expected in natural sediment (Table IV) it is certain that Bi is also a contaminant from an unknown source.

TABLE IV

Chemical analysis of naturally occurring marine sediments from various environments

Environment	Ba	Sb	Cd	Pb	Zn	Cu	Sn	In	Ag	Bi
Mofjord, West Norway[a]				56	130	25				
Oslofjord, East Norway[b]				158	265	35				
Equatorial Atlantic[c]				36	130	180				
Gulf of Paria[d]	418			26		19	0 75			0.02
Aver. Shale[e]	580	1.5	0.3	20	80	57	6	0.05	0.1	0.01

[a]Taylor, (1972).
[b]Price (1967) (Some contamination of sediments is likely).
[c]Nicholls (1967).
[d]Hirst (1962).
[e]Krauskopf (1965).

It may have been more prevalent as a waste product during the early years of industrial activity in Sörfjord.

If the high metal concentrations in the sediments of the southern parts of Sörfjord originate as a simple dispersal of waste (solid) matter from a specific source, certain element ratios in the sediment should be similar to those in the effluents. Elemental ratios in the sediment have been calculated from least squares regressions of the plotted data shown in Figures 2, 3 and 4. Table V shows that while the Zn/Pb ratios of sediment and effluent are very similar, the Cd/Zn and Cu/Zn ratios are different. Relative to Zn the surface sediments have a three fold increase in Cd and Cu over that in the effluent.

TABLE V

Element relationships in surface sediment and effluent

Element	Effluent	Surface sediment
Cu/Zn	0.05	0.175
Cd/Zn	0.005	0.013
Pb/Zn	0.75	0.77

The reason for this change is not known, but may be the result of:

(a) Change in the composition of waste residues with time, or differences in the relative amounts of soluble to insoluble residues discharged into the fjord.

(b) Variations in the particle size of specific metallic residues which will facilitate a greater dispersal of some metals over others.

(c) Differential solubilization of certain metals in what must be regarded as a most unusual marine environment, where pH values of 3.7 were recorded in the surface water.

(d) Selective fixation of certain metals like Cd and Cu onto the surface of the sediment.

In view of the association of certain metals in biological systems (Nicholls *et al.* 1959; Bowen, 1966) the last suggestion is of considerable interest as fixation of metals

at the surface may involve some uptake by organic substances. Also since specific metals (e.g., Hg) can be complexed with organic substances (Jensen and Jernlöv, 1967) and taken up in food chains (Jernlöv and Lann, 1971) we think it will be important to study the association of metals in the Sörfjord sediments with the level and type of organic matter present.

In view of the preliminary results presented here we are resolved to measure metal concentrations in the water, in the suspended matter and also in various organisms that occur in the fjord, so that a better understanding of the pathways of contaminating metals in marine systems can be gained.

Acknowledgments

This research was supported by grants from N.E.R.C. Great Britain and Miljövenkomiteen of Odda. We are particularly grateful to the latter and to the industrial organizations in Odda for information on the levels of contaminants entering the fjord, and their generous cooperation and facilities given to us.

We wish to thank K. Sögnen, G. Maisey, and J.H. Taylor for the help given to us during the field work.

References

Bowen, H. J. M.: 1966, *Trace Elements in Biochemistry*, Academic Press, London and New York, 271 pp.
Haya, T. R., Ichwatavi, R., and Ichikum, H.: 1963, *J. Oceanog. Soc. Japan* **19**, 20.
Hirst, D. M.: 1962, *Geochim. Cosmochim. Acta*, **26**, 1147.
Irukayma, K., Kondo, T., Kai, F., and Fujiki, M.: 1961, *Kumatoto Med. J.* **14**, 157.
Jensen, S. and Jernlöv, A.: 1967, *Nature* **223**, 753.
Jernlöv, A. and Lann, H.: 1971, *Oikos* **22**, 403.
Jones, J. R. E.: 1938, *Brit. J. Exp. Biol.* **15**, 397.
Krauskopf, K. B.: 1965. *Introduction to Geochemistry*, McGraw-Hill Book Co. New York, 721 pp.
Mullin, J. B. and Riley, J. P.: 1956, *J. Mar. Res.* **15**, 103.
Nicholls, G. D.: 1967, *Mar. Geol.* **5**, 539.
Nicholls, G. D., Curl, H. Jr., and Bowen, V. T.: 1959, *Limnol. Oceanogr.* **4**, 472.
Price, N. B.: 1967, *Mar. Geol.* **5**, 511.
Reynolds, R. C., Jr.: 1963, *Amer. Mineral.* **48**, 1.
Saelem, O. H.: 1967, Edt. Lauff, G. H. *Amer. Assoc. Adv. Sci.* Publ. No. 83.
Taylor, J. H.: 1972, private communication.

Particulate Metals in Waters of Sörfjord West Norway

By J M Skei, N B Price and S E Calvert,
Grant Institute of Geology, University of Edinburgh,
West Mains Road, Edinburgh EH9 3JW, Great Britain.

The purpose of the present investigation was to determine the levels of suspended particulate copper (Cu), zinc (Zn) and lead (Pb) in the waters of Sörfjord, West Norway, and to use this information to trace the dispersal pattern of metal-containing industrial waste which is discharged into the fjord at its southern extremity, near the town of Odda. The investigation has shown that concentrations of these metals in the fjord, especially Zn and Pb, are up to two or three times higher than in natural sea water. Metals have been detected in both surface and subsurface waters 40 km away from the area of metal discharge. Considering the hydrography and the relationship of Zn and Pb in different waters, it seems possible to draw the conclusion that two distinct bodies of contaminated water outflow from the fjord. However, during periods of high river runoff, the dispersal of metals in subsurface waters will be different, and at such times we predict that pollution of the inner fjord will be greatest.

We have investigated the chemical composition of suspended particulate matter in a number of uncontaminated marine environments. This report concerns our study of the composition of sea water in Sörfjord, West Norway, which is heavily contaminated by metals at its northern end (1). This investigation is intended to show, from the concentration of Zn, Pb and Cu in suspended particulate matter, the effect of metal pollution within the entire fjord and the dispersal of these metals in the fjord's surface and subsurface waters.

Sörfjord is a north-south trending extension of Hardangerfjord, 1–2 km wide and 40 km long (Figure 1). The fjord has a step-like profile with several flat areas, with a maximum depth of 390 m shallowing southwards towards Odda where the water is approximately 50 m deep. Most runoff enters the fjord close to Odda via the River Opo while smaller amounts are supplied from the sides, especially from the west where streams drain the Folgefonni glacier.

Three industrial plants are situated near Odda and produce a variety of products (1). Industrial waste, as solids and solutions from a zinc smelting plant, is led into the fjord at depths of 0 to 25 m; the respective daily amounts of discharge of Cu, Pb and Zn are 300, 4,500 and 6,000 kg/day.

The salinity (S) and temperature (T) of the water were measured for the stations in Figure 1 during August, 1971. Profiles of S and T for three of these stations (26, 29 and 32) are shown in Figure 2. Surface salinities are low everywhere (~5‰) but rapidly increase with depth to ~34‰ within the upper 4 m or 5 m of water. A small but distinct increase of temperature is seen from 0 m to 4 m, below which there is a gradual decrease until fairly constant values are reached below 70 m. The temperatures of subsurface waters in the north are lower than in waters of equivalent depth in the south.

Samples of particulate matter in the water were collected during August, 1971, from eight stations in Sörfjord which were positioned along a median line extending from Odda northwards to the entrance of the fjord. Samples of about 5 l of water were collected in polyvinyl chloride/nylon water bottles. After transfer to prewashed polyethylene containers the water was suction filtered in air through preweighed, 47 mm diameter, 0.45 Sartorius membrane filters (2). Quantities of Zn and Cu and Pb in the particulate matter expressed as μg metal/l water were determined by X-ray emission analysis (3). Standards were prepared using water insoluble salts of Cu, Zn and Pb and calibration curves were obtained from the net peak intensities of the Cu Kα, Zn Kα and Pb Lα radiations against a series of synthetic standards. The precision of the

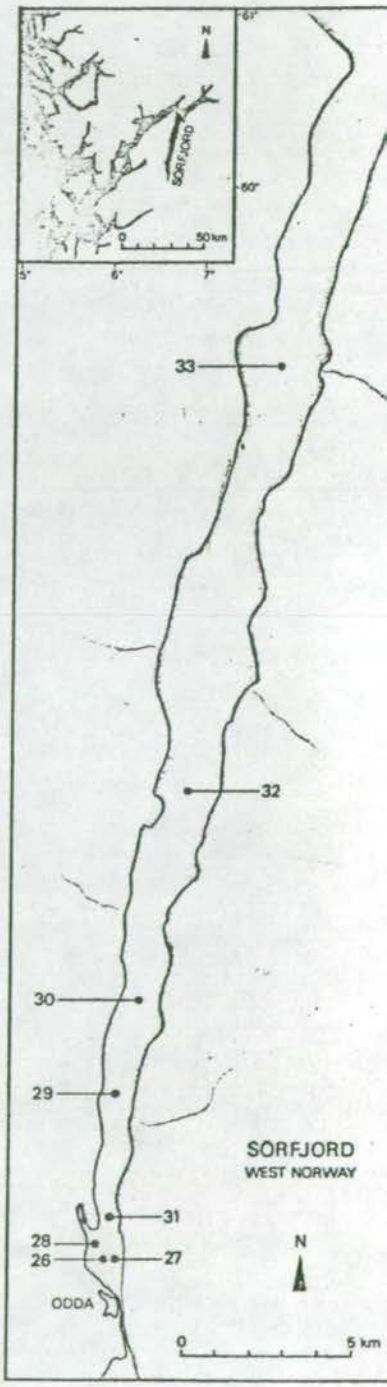
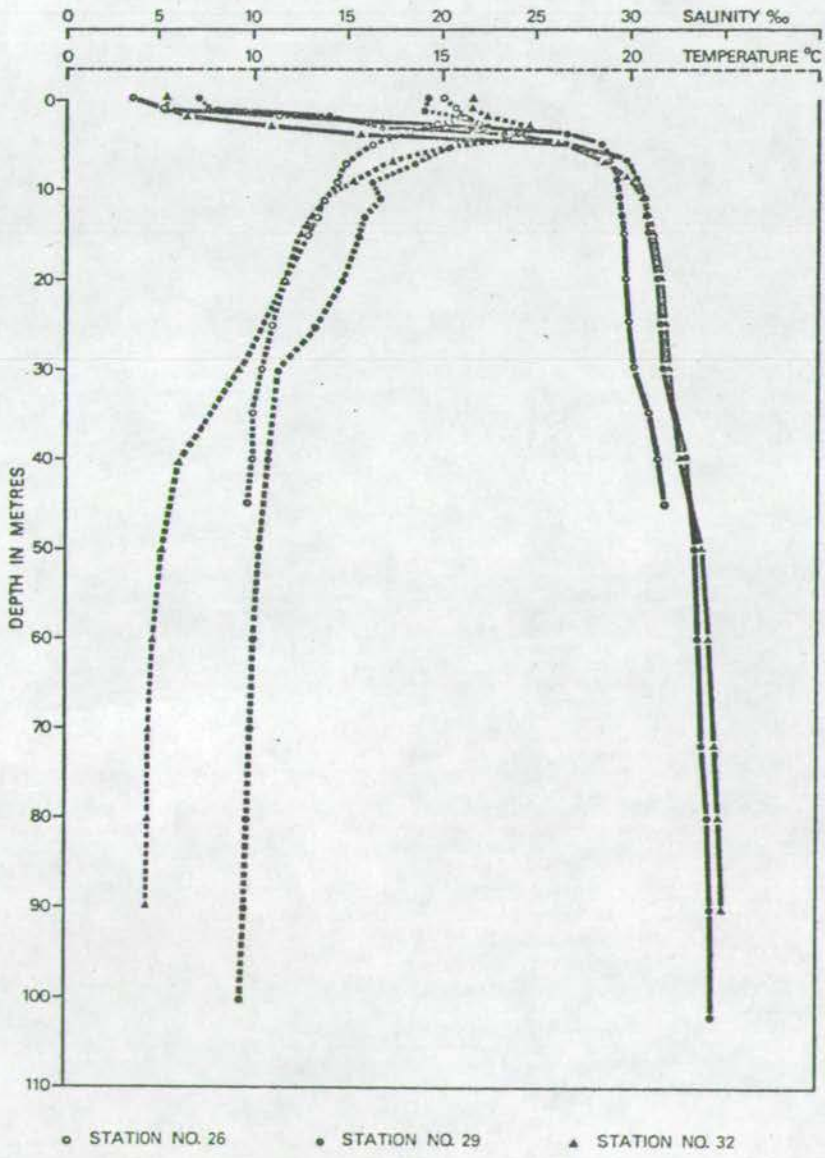


Figure 1. Sörfjord is 40 km long and 1–2 km wide. Industrial waste containing Cu, Zn and Pb enters the fjord about the town of Odda. Water sampling stations are shown. Main water influence is Opo river. In addition water inflow by several streams from Folgefonni glacier west of Sörfjord.

Figure 2. Vertical profiles of temperature and salinity, sampled at three water stations in Sörfjord, West Norway. Density structuring of water (δ t) is primarily controlled by salinity. T°C = ..., S‰ = ____



method was estimated to be Cu = 13 percent, Pb = 8 percent and Zn = 3 percent.

The content of Zn, Pb and Cu in the particulate matter of different waters in the fjord (Table 1) show that the concentration range for these elements is very great, that is 1.32–51.29 μg/l Zn, 0.7–58.05 μg/l Pb and < 0.1–2.04 μg/l Cu. Most water in the fjord show concentrations that are far higher ($1–5 \times 10^2$) than those occurring in normal sea water. For instance, concentrations of 0.1 to 0.2 μg/l Zn and 0.1 to 0.25 μg/l Cu have been quoted for particulate matter in the Gulf of Maine (2). A similar value of Cu (*ie* 0.3 μg/l) has been determined in water of the English Channel (4). Particulate Pb in other uncontaminated Norwegian fjords is below 0.1 μg/l (5) and this figure is taken as an estimate for normal waters. Contributions of Cu from terrigenous and biological sources to the total particulate matter measured are likely to be much more important than contributions of Zn and Pb from the same sources. Natural contributions of Zn and Pb as a proportion of the total particulate matter measured are insignificant.

In the inner fjord stations (26, 27, 28, 29 and 31) maximum values of Zn and Pb occur at variable depths below the surface, although surface values are much in excess of those found in natural waters. Stations in the north (30, 32 and 33) show higher values for these metals in the surface water (0–5 m) while at depth the values can decrease to near-natural levels. In the case of Cu, although concentrations are much lower than for Pb and Zn, some high values are present at intermediate water depths in the southernmost part of the fjord. In the northern stations the highest Cu concentrations occur at the surface.

The high concentration at different depths in the southern parts of the fjord probably results from the proximity of water sampling to points of industrial discharge of metal effluents. One may therefore expect some lateral dispersal of this material in the fjord. Horizontal variations in metal concentrations, especially in the northern parts of the fjord, suggest that the fjord is pervaded by metal waste throughout. Metal concentrations both in the surface (0–5 m) and subsurface waters down to at least 30 m depth, show a general northward decrease. A similar pattern of decreasing metal concentration in waters sampled at progressively greater distances from the southern California coast has also been observed (6) and is likewise thought to be due to the dispersal of effluent materials.

Table 1. Concentrations of particulate Cu, Pb and Zn in the waters of Sörfjord, West Norway (μg/l)

Station	Depth m	Cu	Pb	Zn	Zn/Pb ratio
26	0	1.02	8.92	16.57	1.86
	2	0.37	3.59	11.12	3.10
	30	0.53	16.59	11.15	0.67
	40	0.52	27.92	14.64	0.52
27	0	0.68	4.18	6.21	1.49
	1	0.87	2.82	9.55	3.39
	5	1.00	14.64	41.45	2.83
	10	0.60	13.72	17.85	1.30
	20	1.89	11.14	36.36	3.26
	30	0.26	14.38	17.80	1.24
28	0	1.32	14.14	25.68	1.82
	5	1.57	22.93	51.29	2.24
	10	2.04	32.06	–	–
	15	1.45	36.98	35.91	0.97
	20	1.14	42.66	30.80	0.72
31	0	0.51	3.08	22.77	7.39
	5	0.61	9.74	–	–
	10	0.47	18.40	21.26	1.16
	20	1.57	58.05	34.82	0.60
29	0	0.25	4.79	8.66	1.81
	5	0.76	3.11	–	–
	10	0.66	9.99	14.02	1.40
	20	0.14	6.06	7.32	1.21
	50	0.41	14.93	9.23	0.62
30	0	0.84	7.33	10.79	1.47
	5	0.58	2.99	–	–
	10	0.10	3.16	5.19	1.64
	30	bd	1.21	3.61	2.98
	80	0.15	3.55	2.85	0.80
	150	bd	4.39	1.67	0.38
32	0	0.11	6.32	20.34	3.22
	10	bd	0.70	3.66	5.23
	80	bd	2.23	1.32	0.58
33	0	0.13	3.65	–	–
	10	bd	bd	2.07	–
	30	bd	bd	1.41	–

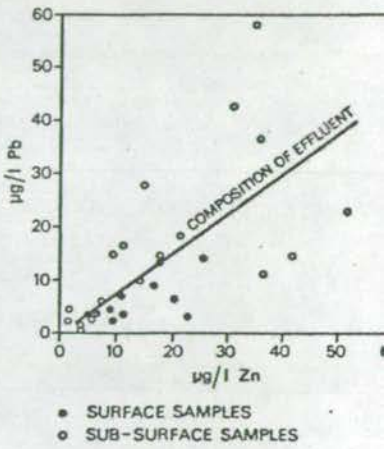
bd = below detection
Detection limits are: Cu = 0.1 μg/l, Pb = 0.1 μg/l, Zn = 0.15 μg/l

The relationship of Zn to Pb is shown in Figure 3 and Table 1 and is different in surface and subsurface particulate matter. Zn/Pb ratios at the surface are distinctly higher than in the effluent (Figure 3), while in most subsurface waters they are lower. This is especially seen in particulate matter from samples taken at the northern stations. The reason for this change in ratio is not known. Possibly, solid effluents introduced into surface waters differ in composition from those discharged at depth. Alternatively, there may be preferential solution of either particulate Zn or Pb in waters of different physicochemical character.

The pattern of dispersal of particulate metals in the waters of fjord depends essentially on its circulation. Water circulation in fjords is of a modified estuarine type, and is distinguished by the primary circulation taking place in the upper layers of water because river runoff dominates over that of tidal mixing (7, 8). The salinity distribution for Sörfjord shown in Figure 2 is typical for fjords in general. However, mean circulation under conditions of large and small runoff is different (7). During periods when high runoff exerts a greater influence than tidal mixing (eg May–June), surface outflow is restricted to the uppermost few meters of water; a compensating strong inflow occurs immediately beneath (7). In periods of low runoff, similar to that occurring during August, 1971, temperature/salinity profiles assume a trend as seen in Figure 2 (7). Now outflow can occur within water extending down to several tens of meters, although a marked velocity shear may occur in the upper few meters of water.

The norhward decrease in concentrations of particulate Pb, Zn and possib Cu and the difference in the Zn-Pb rel tionship between surface and subsurfac waters implies dispersal of waste in a outflow which extends into Hardange fjord. Moreover, it appears that there an outflow of at least two distinct bodi of water: 1) a surface layer characterize by high Zn/Pb ratios flowing with greater velocity over 2) a subsurfac layer where the particulate matter ha low Zn/Pb ratios. However, at times high runoff, the outflow situation change Metal discharged into the subsurfac water, instead of being dispersed in a outflow, are carried southwards toward Odda by an inflow and causes excessiv contamination there.

Figure 3. The relationship of Zn to Pb in t particulate matter of Sörfjord. That in surfa waters has higher Zn/Pb ratios than the me waste (dotted line), while Zn/Pb ratios in mo subsurface samples are lower.



References and Notes:

1. J M Skei, N B Price, S E Calvert and H Holtedahl, *Water, Air and Soil Pollution* 1, 452–461 (1972).
2. D W Spencer and P L Sachs, *Marine Geology* 9, 117–136 (1970).
3. N B Price and S E Calvert, *in prep.*
4. B A Loveridge, G W C Milner, G A Barnett, A Thomas and W M Henry, *United Kingdom Atomic Energy Authority Repr.* No. 3323, p 42 (1960).
5. J H Taylor, *personal communication* (1972).
6. R R Brooks, R J Presley and I R Kaplan, *Talanta* 14, 809–816 (1967).
7. M Rattray in *Estuaries*, Ed G H Lauff, (American Association for the Advancemer of Science Publ No. 83, 1967) pp 52–62.
8. O H Saelen, *in ibid*, pp 63–70.
9. The study was supported by a grant fro the Natural Environment Research Counc of Great Britain. Miljövernkomiteen o Odda, Norway, provided some of the fiel expenses.
10. We thank Professor H Holtedahl of th University of Bergen for use of the R/V Hans Reuch and also K Sögnen, G Maise and J H Taylor for the help given to u during the field work.
11. Received July 6, 1972.

ACKNOWLEDGEMENTS

I am deeply indebted to Professor Hans Holtedahl for originally suggesting the area of study and for encouragement during the progress of work. Further I would like to thank him for making available the R. V. "Hans Reusch" for five cruises to Sörfjorden during the period 1971 to 1974. The help of Messrs. K. Sögnen, G. H. Maisey, H. Isachsen, O. Elholm, G. Wilson and Dr. J. H. Taylor during sampling is greatly appreciated. I would also like to thank Mr. K. Kristensen, Lofthus for kindly providing me with facilities to set up a laboratory ashore during the cruises. I wish to thank cand. real. H. Svendsen (University of Bergen) for kindly allowing me to use his data on dissolved oxygen for 1972. I am also indebted to Dr. D. H. Jones (Institute for Marine Environmental Research, Edinburgh) for identifying various species of plankton and to Mr. I. Goodall for providing me with scanning electron micrographs of suspended particulate matter.

I am grateful for the facilities placed at my disposal in the Grant Institute of Geology by Professor G. Y. Craig. I also appreciate useful analytical advice from Messrs. M. J. Saunders and G. R. Angell. Thanks also are due to Messrs. C. Chaplin and R. Devine for carrying out the photographic work for the thesis. I greatly appreciate useful suggestions relating to the research from Dr. S. E. Calvert during 1971-72 and from Dr. E. R. Sholkovitz during 1973-75.

I most sincerely wish to thank Dr. N. B. Price for his dedicated supervision and objective criticism of the thesis and for his encouragement, not only in scientific matters, but also personally during periods of financial difficulties.

I am deeply indebted to my wife Anne-Grete for patiently accepting a deprived social life during the years of study.

I am grateful to Mr. G. S. Holmes for reading the manuscript and to Miss M. A. R. Lumsden for neatly typing the thesis.

Finally I gratefully acknowledge the receipt of financial support to carry out the field work, from the Miljövernkommiteen i Odda (Environmental Committee of Odda, Norway), Norges Almenvitenskaplige Forskningsråd (D. 41. 31-18) and the Natural Environment Research Council, Great Britain (N. B. Price). The receipt of an Edinburgh University Postgraduate Studentship for a period of three years is greatly appreciated.

BIBLIOGRAPHY

AARTHUN, K.E. 1961. Submarine daylight in a glacier-fed Norwegian fjord. The natural history of the Hardangerfjord. Sarsia, 1, 7-20.

AHLMANN, H.W. 1919. Geomorphological studies in Norway. Geogr. Annaler, 1, 1 20.

ALLEN, G.P. and P. CASTAING. 1973. Suspended sediment transport from the Gironde estuary on to the continental shelf. Mar. Geol., 14, M47-53.

ANDERSON, J.J. and A. H. DEVOL. 1973. Deep water renewal in Saanich Inlet, an intermittently anoxic basin. Estuar. Coast. Mar. Sci., 1, 1-10.

ATKINSON, L.P. and U. STEFANSSON. 1969. Particulate aluminium and iron in sea water off southeastern coast of the United States. Geochim. Cosmochim. Acta., 33, 1449-1453.

BANSE, K. 1963. A gravimetric method for determining suspended matter in seawater using millipore filters. Deep-Sea Res., 409, 639-642.

BASSIN, N.J., J. E. HARISS and A. N. BOUMA. 1972. Suspended matter in the Caribbean Sea; a gravimetric analysis. Mar. Geol., 12, M1-5.

BEER, R.M. and D. S. GORSLINE. 1971. Distribution, composition and transport of suspended sediment in Redondo Submarine Canyon and vicinity (California). Mar. Geol., 10, 153-175.

BETZER, P.R. and M. E. Q. PILSON. 1970. Concentrations of particulate iron in Atlantic open-ocean water. J. Mar. Res., 28, 251-267.

BOGDANOV, Y.A. and M. G. SHAPOSHNIKOVA. 1971. Content of suspended organic matter in the tropical Pacific. Oceanology, 11, 563-568.

BORNHOLD, B.D., J. R. MASCLE and K. HARADA. 1973. Suspended matter in surface waters of the eastern Gulf of Guinea. Mar. Geol., 14, M21-31.

BOYLE, E. and J. M. EDMOND. 1975. Copper in surface waters south of New Zealand. Nature, 253, 107-109.

BRAARUD, T., B. FØYN HOFSVANG, P. HJELMFOSS and A. A.-K. ØVERLAND. 1974. The natural history of the Hardangerfjord. 10. The phytoplankton cycle in the fjord waters and in the off-shore coastal waters. Sarsia, 55, 63-98.

BRULAND, K. W., K. BERTINE, M. KOIDE and E. D. GOLDBERG. 1973. History of metal pollution in Southern California coastal zone. Environ. Sci. Technol., 8, 425-436.

BRYAN, G. W. 1971. The effects of heavy metals (other than mercury) on marine and estuarine organisms. Proc. Roy. Soc. Lond. B., 177, 389-410.

BURELL, D. C. and C. M. HOSKIN. 1970. Cyclic sedimentation patterns within active glacial fjords. University of Alaska, Inst. of Mar. Sci., Rep. No. R70-3, 17pp.

BURELL, D. C. and R. S. HADLEY. 1971. Suspended sediment size fractionation within a fjord-estuary: application of electronic counting techniques. Trans. Am. Geophys. Union, 52, 853.

BUTTERWORTH, J., P. LESTER and G. NICHLESS. 1972. Distribution of heavy metals in the Severn Estuary. Mar. Poll. Bull., 3, 72-74.

CAMERON, W. M. and D. W. PRITCHARD. 1963. Estuaries. In: HILL, M. N. (ed.) The Sea. Vol. 2. Wiley, New York. pp 306-324.

CAPUZZO, J. M. and F. E. ANDERSON. 1973. The use of modern chromium to determine estuarine sedimentation rates. Mar. Geol., 12, 225-237.

CARMODY, D. J., J. B. PEARCE and W. E. YASSO. 1973. Trace metals in sediments of New York Bight. Mar. Poll. Bull., 4, 132-135.

CARSTENS, T. 1970. Turbulent diffusion and entrainment in two-layer flow. Proc. Amer. Soc. Civil. Eng., WW1, 97-104.

CHESTER, R. 1965. Elemental geochemistry of marine sediments. In: RILEY, J. P. and G. SKIRROW (eds.) Chemical Oceanography, Vol. II. Academic Press, London. pp 23-80.

CHOW, T. J. and A. W. MANTYLA. 1965. Inorganic nutrient anions in deep ocean waters. Nature, 206, 383-385.

CHOW, T.J., K. W. BRULAND, K. BERTINE, A. SOUTAR, M. KOIDE and E. D. GOLDBERG. 1973. Lead pollution: Records in Southern California coastal sediments. Science, 181, 551-552.

COONLEY, L.S., E. B. BAKER and H. D. HALLAND. 1971. Iron in the Mullica river and in Great Bay, New Jersey. Chem. Geol., 7, 51-63.

COOPER, L.H.N. 1935. Iron in the sea and in marine plankton. Proc. Roy. Soc. Lond. B., 118, 419-438.

_____ 1952. Factors affecting the distribution of silicate in the North Atlantic Ocean and the formation of North Atlantic deep water. J. Mar. Biol. Ass. U.K., 30, 511-526.

CRANSTON, R.E. and D. E. BUCKLEY. 1972. The application and performance of microfilters in analyses of suspended particulate matter (unpubl. manuscript) Bedford Inst. Oceanogr. Rep. Ser., BI-R-72-7. 14pp.

D'ANGLEJAN, B.F. and E. C. SMITH, 1973. Distribution, transport and composition of suspended matter in the St. Lawrence estuary. Can.J. Earth Sci., 10, 1380-1396.

DOFF, D.H. 1970. The geochemistry of Recent oxic and anoxic sediments of Oslo Fjord, Norway. Unpubl. Ph.D. Thesis, Univ. of Edinburgh, pp 212.

DYRSSEN, D., C. PATTERSON, J. UI. and G. F. WEICHART. 1972. Inorganic chemicals. In: GOLDBERG, E.D. (ed.) A guide to marine pollution. Gordon and Breach Science Publ., London. pp 41-58.

EDMOND, J.M. 1970. High precision determination of titration alkalinity and total carbon dioxide content of seawater by potentiometric titration. Deep-Sea Res., 17, 737-750.

ENVIRONMENTAL COMMITTEE REPORT. 1973. Resipient-undersökelser i Sörfjorden 1972. Odda, Norway. 250pp.

ERLENHEUSER, H., E. SUESS and H. WILLKORN. 1974. Industrialization affects heavy metal and carbon isotope concentrations in recent Baltic Sea sediments. Geochim. Cosmochim. Acta., 38, 823-842.

EWING, M., S. L. EITTREIM, J. I. EWING and X. Le PICHON. 1971. Sediment transport and distribution in the Argentine basin. 3. Nepheloid layer and processes of sedimentation. Phys. Chem. Earth, 8, 49-77.

FANNING, K. A. and D. R. SCHINK. 1969. Interaction of marine sediments with dissolved silica. Limnol. Oceanogr., 14, 59-69.

FOLGER, D. W., R. H. MEADE, B. F. JONES and R. L. CORY. 1972. Sediments and waters of Somes Sound, a fjord-like estuary in Maine. Limnol. Oceanogr., 17, 394-402.

FUJITA, T. 1971. Concentration of major chemical elements in marine plankton. Geochem. J., 4, 143-156.

GADE, H. G. 1973a. Oceanografiske observasjoner i Fensfjorden 1972. Bergen, Norway. 12pp.

_____ 1973b. Deep water exchanges in a sill fjord: a stochastic process. J. Phys. Oceanogr., 3, 213-219.

GARNER, D. M. 1964. The hydrology of Milford Sound. In: SKERMAN, T. M. (ed.) Studies of a southern fjord. New Zealand Oceanogr. Inst. Mem. No. 17. pp 25-33.

GEORGE, J. D. 1970. Sub-lethal effects on living organisms. Mar. Poll. Bull., 1, 107-109.

GOLDBERG, E. D. 1970. Chemical invasion of ocean by man. In: LAPEDES, D. N. Yearbook of Science and Technology. McGraw-Hill. pp 64-73.

GOLDSCHMIDT, V. M. 1954. Geochemistry. Oxford Univ. Press. 730pp.

GRAHAM, H. W. 1941. An oceanographic consideration of the dinoflagellate genus Ceratium. Ecol. Monogr., 11, 99-117.

GRILL, E. V. and F. A. RICHARDS. 1964. Nutrient regeneration from phytoplankton decomposing in seawater. J. Mar. Res., 22, 51-69.

HALLBERG, R. O. 1973. The microbiological C-N-S cycles in sediments and their effect on the ecology of the sediment-water interface. Oikos Suppl., 15, 51-62.

HARDER, H. 1974. Illite mineral synthesis at surface temperatures. Chem. Geol., 14, 241-253.

HAUG, A., S. MELSOM and S. OMANG. 1974. Estimation of heavy metal pollution in two Norwegian fjord areas by analysis of the brown algae Ascophyllum nodusum. Environ. Poll., 7, 179-192.

HAVRE, G. N., B. UNDERDAHL and C. TROSDAHL. 1973. Analyse av elementene kvikksölv, kadmium, bly og sink i marint animalsk materiale fra Sörfjorden i Hardanger. In: Environmental Committee Report. Odda, Norway. 14pp.

HIRST, D. M. 1962. The geochemistry of modern sediments from the Gulf of Paria. I. The relationship between the mineralogy and the major elements. Geochim. Cosmochim. Acta., 26, 309-334.

HOLTEDAHL, H. 1965. Recent turbidites in the Hardangerfjord, Norway. Proc. 17th Symp. Colston Res. Soc. (Bristol). pp 107-141.

HOSKIN, C. M. and D. C. BURRELL. 1972. Sediment transport and accumulation in a fjord basin, Glacier Bay, Alaska. J. Geol., 80, 539-551.

ISAYEVA, A. B. 1971. Relation between titanium and iron in the sediments of the Indian Ocean. Geochem. Int., 8, 186-194.

JACOBS, M. B. and M. EWING. 1965. Mineralogy of particulate matter suspended in seawater. Science, 149, 179-180.

_____ 1969. Suspended particulate matter: concentration in the major oceans. Science, 163, 380-383.

JACOBS, M. B., E. M. THORNDIKE and M. EWING. 1973. A comparison of suspended particulate matter from nepheloid and clear water. Mar. Geol., 14, 117-128.

JERLOV, N. G. 1953. Influence of suspended and dissolved matter on the transparency of seawater. Tellus, 5, 59-65.

_____ 1955. The particulate matter in the sea as determined by means of the Tyndall meter. Tellus, 7, 218-225.

JONES, J. R. E. 1938. The relative toxicity of salts of lead, zinc and copper to the stickleback and the effect of calcium on the toxicity of lead and zinc salts. Brit. J. Exp. Biol., 15, 394-407.

JOYNER, T. 1964. The determination and distribution of particulate aluminium and iron in the coastal waters of the Pacific North-west. J. Mar. Res., 22, 259-268.

KETCHUM, B. H. 1967. Phytoplankton nutrients in estuaries. In: LAUFF, G. H. (ed.) Estuaries. Am. Ass. Adv. Sci. Publ. 83. Washington, D. C. pp 329-336.

_____ 1969. Eutrophication of estuaries. In: Eutrophication: Causes, Consequences, Corrections. Proc. Symp. National Acad. Sci., Washington, D. C. pp 197-209.

KNAUER, G. A. and J. H. MARTIN. 1973. Seasonal variations of cadmium, copper, manganese, lead and zinc in water and phytoplankton in Monterey Bay, California. Limnol. Oceanogr., 18, 597-605.

KNUDSEN, M. 1901. Hydrographical Tables. G. E. C. Gad Copenhagen. 63pp.

KOLDERUP, N. H. 1960. Hardanger and Sogn. In: SÖMME, A. (ed.) Vestlandet-Geographical Studies. Geogr. Avh., 7, 9-16.

KRAUSKOPF, K. B. 1956. Factors controlling the concentrations of thirteen rare metals in seawater. Geochim. Cosmochim. Acta., 9, 1-32B.

_____ 1957. Separation of manganese from iron in sedimentary processes. Geochim. Cosmochim. Acta., 12, 61-84.

_____ 1967. Introduction to geochemistry. McGraw-Hill, New York. 721pp.

KVALE, A. 1946. Petrologic and structural studies in the Bergsdalen quadrangle. Part I. Petrography. Aarbok Bergens Museum, Mat.-Nat. Ser., No. 1, 201pp.

KVISTAD, J. 1965. Kvartargeologiske og gemorfologiske undersökelser i Sörfjorden. Unpubl. cand. real. thesis, Univ. of Bergen, 85pp.

LEWIS, G. J. Fr. and E. D. GOLDBERG. 1954. Iron in marine waters. J. Mar. Res., 13, 183-197.

MALCOLM, R. L. 1972. Comparison of conditional stability constants of North Carolina humic and fulvic acids with Co(II) and Fe(III). In: NELSON, B. W. Environmental framework of coastal plain estuaries. Geol. Soc. Am. Mem. 133. pp 79-85.

MANDELLI, E. F. 1969. The inhibitory effects of copper on marine phytoplankton. Contr. Mar. Sci., 14, 47-59.

MANHEIM, F. T., R. H. MEADE and G. C. BOND. 1970. Suspended matter in surface waters of the Atlantic continental margin from Cape Cod, Massachusetts to the Florida Keys. Science, 167, 371-376.

MARTIN, J.H. 1970. The possible transport of trace metals via moulted copepod exoskeletons. Limnol. Oceanogr. 15, 756-761.

MARTIN, J.H. and G. A. KNAUER. 1973. The elemental composition of plankton. Geochim. Cosmochim. Acta., 37, 1639-1653.

McALISTER, W.B., M.Fr. RATTRAY and C. A. BARNES. 1959. The dynamics of a fjord estuary: Silver Bay, Alaska. Dep. Oceanogr. Tech. Rep. No. 62. Univ. of Washington, Seattle, Washington. 36pp.

McLERRAN, G.J. and C. W. HOLMES. 1974. Deposition of zinc and cadmium by marine bacteria in estuarine sediments. Limnol. Oceanogr., 19, 998-1000.

MEADE, R.H. 1968. Relations between suspended matter and salinity in estuaries of the Atlantic seaboard, U.S.A. Publ. Int. Ass. Sci. Hydrol., 4, 96-109.

_____ 1972. Transport and deposition of sediments in estuaries. In: NELSON, B.W. Environmental framework of coastal plain estuaries. Geol. Soc. Am. Mem. 133, pp 91-121.

MENZEL, D.W. and J. H. RYTHER. 1964. The composition of particulate organic matter in the western North Atlantic Limnol. Oceanogr., 9, 179-186.

METCALF, W.G. 1969. Dissolved silicate in the deep North Atlantic. Deep-Sea Res. Suppl., 16, 139-145.

MORRIS, A.W. 1971. Trace metal variations in seawater of the Menai Straits caused by a bloom of Phaecystis. Nature, 233, 427-428.

MURRAY, J.W. 1975. The interaction of metal ions at the manganese dioxide-solution interface. Geochim. Cosmochim. Acta., 39, 505-521.

NELSON, L.M. 1970. A method of estimating annual suspended-sediment discharge. U.S. Geol. Surv. Prof. Paper, 700-C, 233-236.

NESTEROVA, I.L. 1960. Chemical composition of the suspended and dissolved loads of the Ob river. Geochem. Int., 4, 424-431.

NICHOLLS, G.D., H. Fr. CURL and V. T. BOWEN. 1959. Spectrographic analysis of marine plankton. Limnol. Oceanogr., 4, 472-478.

NICHOLLS, M. M. 1972. Sediments of the James River Estuary, Virginia. In: NELSON, B. W. Environmental framework of coastal plain estuaries. Geol. Soc. Am. Mem. 133, pp 169-212.

NICHOLS, F. H. 1974. Sediment turnover by a deposit-feeding polychaete. Limnol. Oceanogr., 19, 945-950.

NISSENBAUM, A., B. J. PRESLEY and I. R. KAPLAN. 1972. Early diagenesis in a reducing fjord, Saanich Inlet, British Columbia. I. Chemical and isotopic changes in major components of interstitial water. Geochim. Cosmochim. Acta., 36, 1007-1029.

NUZZI, R. 1972. Toxicity of mercury to phytoplankton. Nature, 237, 38-40.

O'CONNOR, J. T. and C. E. RENN. 1964. Soluble-adsorbed zinc equilibrium in natural waters. J. Am. Water Works Ass., 56, 1055-1061.

PANTIN, H. M. 1964. Sedimentation in Milford Sound. In: SKERMAN, T. M. (ed.) Studies of a southern fjord. New Zealand Oceanogr. Inst. Mem. No. 17. pp 35-47.

PICKARD, G. L. 1961. Oceanographic features of inlets in the British Columbia mainland coast. J. Fish. Res. Bd. Can., 18, 907-999.

_____ 1963. Descriptive physical oceanography: An Introduction. Pergamon Press. 200pp.

_____ 1971. Some physical oceanographic features of inlets of Chile. J. Fish. Res. Bd. Can., 28, 1077-1106.

PICKARD, G. L. and R. W. TRITES. 1957. Fresh water transport determination from the heat budget with applications to British Columbia inlets. J. Fish. Res. Bd. Can., 14, 605-616.

PICKARD, G. L. and K. RODGERS. 1959. Current measurements in Kneight Inlet, British Columbia. J. Fish. Res. Bd. Can., 16, 635-678.

PICKARD, G. L. and L. F. GIOVANDO. 1960. Some observations of turbidity in British Columbia inlets. Limnol. Oceanogr., 5, 162-171.

PIERSON, D. H., P. A. CAWSE, L. SALMON and R. S. CAMBRAY. 1973. Trace elements in the atmospheric environment. Nature, 241, 252-256.

PIPER, D. Z. 1971. The distribution of Co, Cr, Cu, Fe, Mn, Ni and Zn in Framvaren, a Norwegian anoxic fjord. Geochim. Cosmochim. Acta., 35, 531-550.

POSSELT, H. S. and F. J. ANDERSON. 1968. Cation sorption on colloidal hydrous manganese dioxide. Environ. Sci. Technol., 2, 1087-1093.

POSTMA, H. 1967. Sediment transport and sedimentation in the estuarine environment. In: LAUFF, G. H. (ed.) Estuaries. Am. Ass. Adv. Sci. Publ. 83, Washington, D. C., pp 158-179.

PRESTON, A., D. F. JEFFERIES, J. W. R. DUTTON, B. R. HARVEY and A. K. STEELE. 1972. British Isles coastal waters: The concentrations of selected heavy metals in seawater, suspended matter and biological indicators - a pilot survey. Environ. Poll., 3, 69-82.

PRICE, N. B. 1967. Some geochemical observations on manganese-iron oxide nodules from different depth environments. Mar. Geol., 5, 511-538.

_____ 1973. Chemical diagenesis in sediments. Woods Hole Oceanogr. Inst. Tech. Rep., WHOI-73-39, 73pp.

_____ 1974. Major element composition of suspended particulate matter in the waters of Cariaco Trench, Venezuela. Deep-Sea Res., in press.

PRICE, N. B. and S. E. CALVERT. 1973. A study of the geochemistry of suspended particulate matter in coastal waters. Mar. Chem., 1, 169-189.

PRICE, N. B. and J. M. SKEI. 1975. Areal and seasonal variations in the chemistry of suspended particulate matter in a deep water fjord. Estuar. Coast. Mar. Sci., in press.

PRITCHARD, D. W. 1955. Estuarine circulation patterns. Proc. Am. Soc. Civil Eng., 81, No. 717.

_____ 1959. The movement and mixing of contaminants in tidal estuaries. Proc. 1st Int. Conf. Waste Disposal Mar. Environ. pp 512-525.

RATTRAY, M. Jr. 1967. Some aspects of the dynamics of circulation in fjords. In: LAUFF, G. H. (ed.) Estuaries. Am. Ass. Adv. Sci. Publ. 83, Washington, D. C., pp 52-62.

REDFIELD, A.C. 1955. The hydrography of the Gulf of Venezuela. Deep-Sea Res. Suppl., 3, 115-133.

REID, J.L. 1965. Intermediate waters of the Pacific Ocean. The John Hopkins Oceanogr. Studies No. 2, 85pp.

REVELLE, R.R., T. R. FOLSOM, E. D. GOLDBERG and J. D. ISAACHS. 1955. Nuclear science and Oceanography. Proc. 1st Int. Conf. Peaceful Uses of Atomic Energy, New York, 13, 371-380.

REYNOLDS, R.C. Jr. 1963. Matrix corrections in trace element analysis by X-ray fluorescence: estimation of the mass absorption coefficients by Compton Scattering. Am. Miner., 48, 1133-1143.

RICHARDS, F.A. 1958. Dissolved silicate and related properties of some western North Atlantic and Caribbean waters. J. Mar. Res., 17, 449-465.

RILEY, G.A. 1951. Oxygen, phosphate and nitrate in the Atlantic Ocean. BullBingham Oceanogr. Coll., 13, 1-126.

RILEY, J.P. and R. CHESTER. 1971. Introduction to Marine Chemistry. Academic Press London. 465pp.

RILEY, J.P. and I. ROTH. 1971. The distribution of trace elements in some species of phytoplankton grown in culture. J. Mar. Biol. Ass. U.K., 51, 63-72.

ROALDSET, E. 1972. Mineralogy and geochemistry of Quaternary clays in the Numedal area, Southern Norway. Norsk Geol. Tidsskr., 52, 335-369.

ROCHFORD, D.J. 1958. Characteristics and flow paths of the intermediate depth waters of the southeast Indian Ocean. J. Mar. Res., 17, 483-504.

ROSE, H.J., I. ADLER and F. J. FLANAGAN. 1963. X-ray fluorescence analysis of the light elements in rocks and minerals. Appl. Spectrosc., 17, 81-85.

RUSNAK, G.A. 1967. Rates of sediment accumulation in modern sediments. In: LAUFF, G.H. (ed.) Estuaries. Am. Ass. Adv. Sci. Publ. 83, Washington, D.C. pp 180-184.

RUSSELL, K.L. 1970. Geochemistry and halmyrolysis of clay minerals, Rio Amico, Mexico. Geochim. Cosmochim. Acta., 34, 893-908.

RUTLAND, R. W. R. and D. S. SUTHERLAND. 1967. The chemical composition of granitic gneisses and sparagmitic metasediments in the Glomfjord region, Northern Norway. Norsk Geol. Tidsskr., 47, 359-375.

SACHETT, W. M. and G. ARRHENIUS. 1962. Distribution of aluminium species in the hydrosphere. I. Aluminium in the ocean. Geochim. Cosmochim. Acta., 26, 955-968.

SAELEN, O. H. 1962. The natural history of the Hardangerfjord. 3. The hydrographical observations 1955-1956. Tables of observations and longitudinal sections. Sarsia, 6, 1-25.

_____ 1967. Some features of the hydrography of Norwegian fjords. In: LAUFF, G. H. (ed.) Estuaries. Am. Ass. Adv. Sci. Publ. 83, Washington, D. C. pp 63-70.

SCHAFFER, L. H. 1967. Solubility of gypsum in seawater and seawater concentrates. J. Chem. Eng. Data, 12, 183-189.

SHEAHAN, J. S. 1971. Effect of gypsum dust on the environment. Min. Process., March, 13-17.

SHELDON, R. W., A. PRAKASH and W. H. SUTCLIFFE, Jr. 1972. The size distribution of particles in the ocean. Limnol. Oceanogr., 17, 327-340.

SIEGEL, A. 1971. Metal-organic interactions in the marine environment. In: FAUST, S. J. and J. V. HUNTER (eds.) Organic compounds in aquatic environments. Marcel Dekker, Inc. New York. 638pp.

SKEI, J. M., N. B. PRICE, S. E. CALVERT and H. HOLTEDAHL. 1972. The distribution of heavy metals in sediments of Sörfjord, West Norway. Water, Air and Soil Poll., 1, 452-461.

SKEI, J. M., N. B. PRICE and S. E. CALVERT. 1973. Particulate metals in waters of Sörfjord, West Norway. Ambio, 2, 122-124.

SLOWEY, J. F. and D. W. HOOD. 1971. Copper, manganese and zinc concentrations in Gulf of Mexico waters. Geochim. Cosmochim. Acta., 35, 121-138.

SPENCER, D. W. and P. L. SACHS. 1970. Some aspects of the distribution, chemistry and mineralogy of suspended matter in the Gulf of Maine. Mar. Geol., 9, 117-136.

SPENCER, D. W., P. G. BREWER and P. L. SACHS. 1972. Aspects of the distribution of trace elements and composition of suspended matter in the Black Sea. Geochim. Cosmochim. Acta., 36, 71-87.

STEELE, J. H., A. D. McINTYRE, R. JOHNSTON, J. G. BAXTER, G. TOPPING and H. D. DOOLEY. 1973. Pollution studies in the Clyde Sea area. Mar. Poll. Bull., 4, 153-157.

STENNER, R. D. and G. NICHLESS. 1974. Distribution of some heavy metals in organisms in Hardangerfjord and Skjerstadfjord, Norway. Water, Air and Soil Poll., 3, 279-293.

STRICKLAND, J. D. H. and T. R. PARSONS. 1968. A practical handbook of seawater analysis. Bull. Fish. Res. Bd. Can., 167, 311pp.

STRÖM, K. M. 1936. Land-locked waters. Hydrography and bottom deposits in badly-ventilated Norwegian fjords, with remarks upon sedimentation under anaerobic conditions. Skr. Norske Vidensk. Akad. Oslo, 7, 85pp.

STUMM, W. and J. J. MORGAN. 1970. Aquatic Chemistry. Wiley, New York. 583pp.

SVENDSEN, H. 1973. Oceanografiske undersökelser i Sörfjorden 1972. Bergen, Norway. 17pp.

SVINES, P. 1970. Hardangerfjordens hydrografi September 1955-September 1956. Unpubl. cand. real. thesis, Univ. of Oslo. 112pp.

SZABO, B. J. 1968. Trace element content of plankton population from the Bahamas. Caribbean J. Sci., 8, 185-186.

TABATA, S. and G. L. PICKARD. 1957. The physical oceanography of Bute Inlet, British Columbia. J. Fish. Res. Bd. Can., 14, 487-520.

TAYLOR, J. H. 1974. The geochemistry of fjords of south-west Norway. Unpubl. Ph. D. thesis, Univ. of Edinburgh. 138pp.

THOMPSON, T. G. and K. T. BARKEY. 1938. Observations on fjord-waters. Trans. Am. Geophys. Union, 19, 254-260.

TUCHOLKE, B. E. 1974. Determination of montmorillonite in small samples and implications for suspended matter studies. J. Sedim. Petrol., 44, 254-258.

TULLY, J. P. 1949. Oceanography and prediction of pulp mill pollution in Alberni Inlet. Bull. Fish. Res. Bd. Can., 83, 169pp.

TULLY, J. P. and A. J. DODIMEAD. 1957. Properties of the water in the Strait of Georgia, British Columbia and influencing factors. J. Fish. Res. Bd. Can., 14, 241-319.

TUREKIAN, K. K. 1969. The oceans, streams and atmosphere. In: WEDEPOHL, K. H. (ed.) Handbook of Geochemistry. Springer-Verlag. pp 297-323.

WALDICHUK, M. 1957. Physical oceanography of the Strait of Georgia, British Columbia. J. Fish. Res. Bd. Can., 14, 321-486.

WINKLER, I. W. 1888. Die Bestimmung der in Wasser Gelösten Sauerstoffes. Ber. der. Dent. Chem. Gesell., 21, 2843-2854.

WORTHINGTON, L. V. and W. G. METCALF. 1961. The relationship between potential temperature and salinity in deep Atlantic water. Rapp. Proc.-Verb. Cons. Int. Explor. Mer., 149, 122-128.

ZIRINO, A. and M. L. HEALY. 1970. Inorganic zinc complexes in seawater. Limnol. Oceanogr., 6, 956-958.